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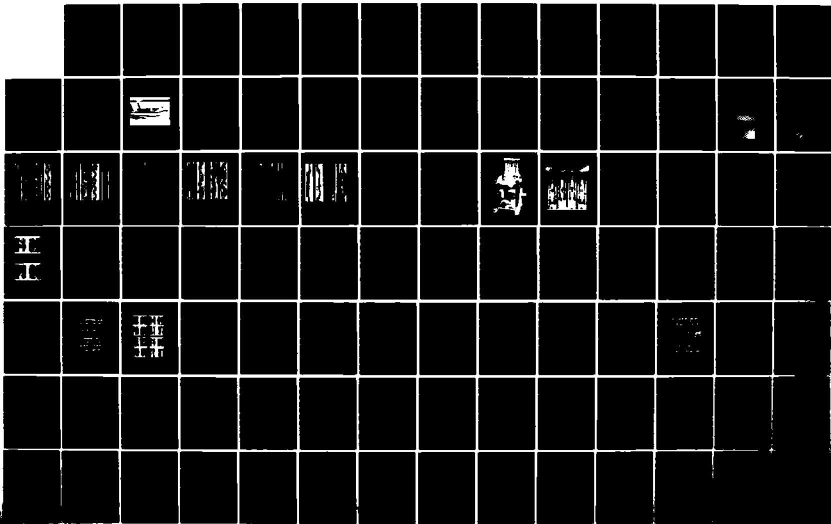

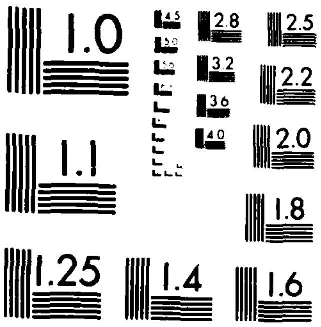

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Bethesda, Maryland 20084

FINGER MATERIALS FOR AIR CUSHION VEHICLES

VOLUME II: BASE FABRICS FOR FINGER MATERIALS

by

Meredith M. Schoppee, John Skelton, and
Mary M. Toney, Albany International
Research Co.

and

William Klemens, DTNSRDC

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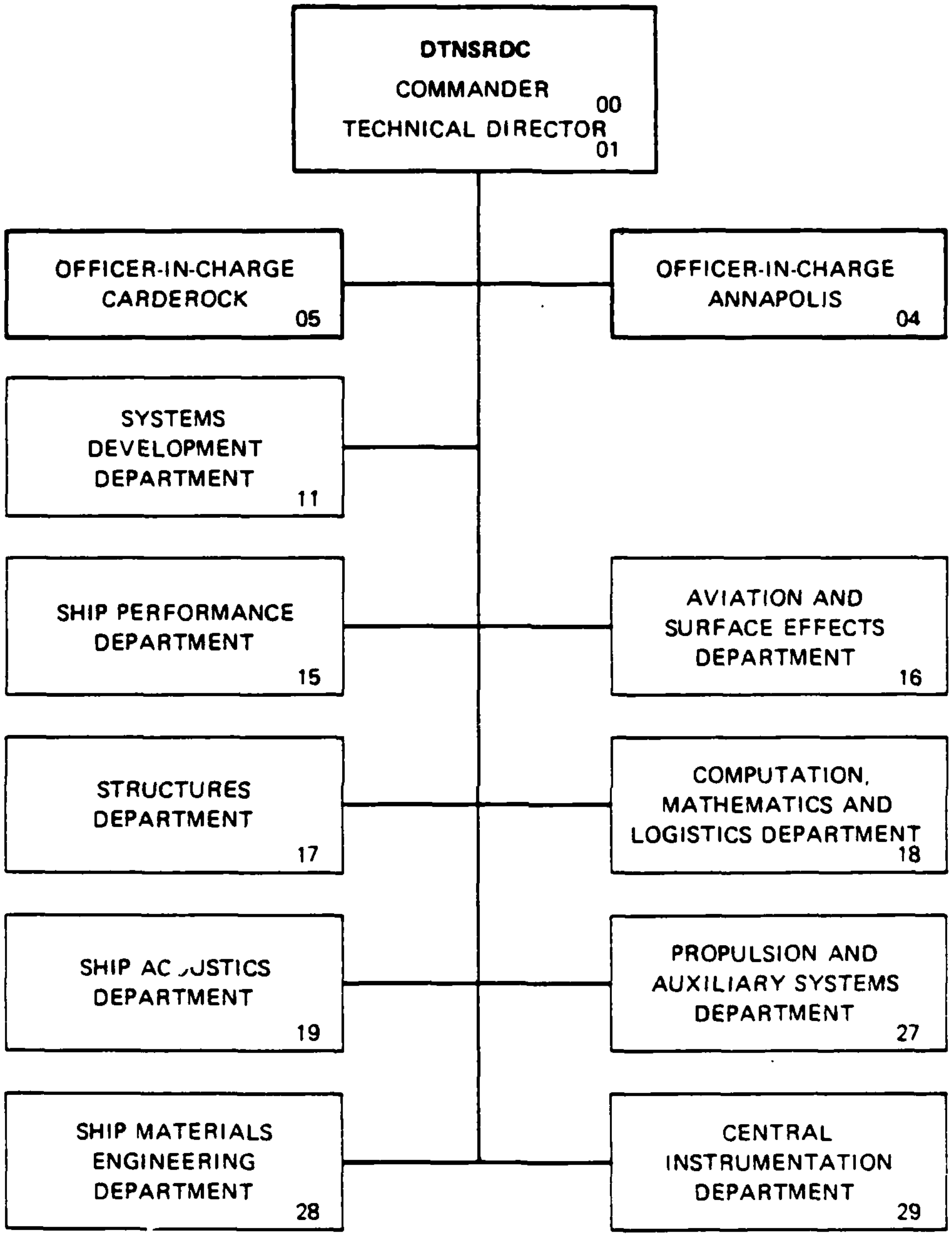

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The short lifetimes of seal/skirt systems on surface effect vehicles (SEV's) severely limit the long-term serviceability of such craft. Therefore, a systematic study was undertaken to evaluate the effects of fabric structure on the performance of rubber/fabric skirt materials under conditions of high-speed, high-curvature flexing. A series of nylon fabrics was designed and manufactured in which the fiber denier, yarn denier, yarn twist, yarn crimp, weave pattern and float length were varied, but in which the tensile strength

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was kept constant throughout. Each of the fabrics was rubber-coated using the same natural rubber/polybutadiene blend and the same coating technique.

A flex-testing apparatus was specially designed and built for flexing the rubber/fabric composite materials in air at an average radius of curvature of 0.28 in. at a cycling frequency of 15 Hz. The lifetimes in flex of the experimental series of fabrics, as indicated by the appearance of flex cracks in the rubber layer, ranged from a low of 140,000 cycles to a high of 21.7 million cycles, a range of over two orders of magnitude.

A factorial analysis of the test results showed that lower yarn denier, lower yarn crimp, and shorter float length (plain-weave) in the fabric substrate offer significant advantages in the ability of the fabric to withstand flexing. ~~The~~ design of three broad fabrics for full-scale skirt trials on the SRN4 craft is described, and recommendations are given for the design of future fabrics.

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ABBREVIATIONS AND SYMBOLS

AI	Albany International Research Co.
D	Distance between parallel supports in flex testing apparatus
dpf	Denier per filament
DTNSRDC	David Taylor Naval Ship Research and Development Center
^oF	Degrees Fahrenheit
g	acceleration of gravity
gal	gallon
gpd	grams per denier
Hz	Hertz
in.	inch
L	Length of fabric being flexed
lb	pound
min	minute
oz	ounce
psf	pounds per square foot
psi	pounds per square inch
r_{min}	minimum radius of curvature
rpm	rotations per minute
S	clockwise direction of twist
SEV	Surface effect vehicle
t	fabric thickness
tpi	twist per inch
yd^2	square yard
Z	counterclockwise direction of twist

ABSTRACT

The short lifetimes of seal/skirt systems on surface effect vehicles (SEV's) severely limit the long-term serviceability of such craft. Therefore, a systematic study was undertaken to evaluate the effects of fabric structure on the performance of rubber/fabric skirt materials under conditions of high-speed, high-curvature flexing. A series of nylon fabrics was designed and manufactured in which the fiber denier, yarn denier, yarn twist, yarn crimp, weave pattern and float length were varied, but in which the tensile strength was kept constant throughout. Each of the fabrics was rubber-coated using the same natural rubber/polybutadiene blend and the same coating technique.

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ADMINISTRATIVE INFORMATION

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The authors thank their colleagues at Albany International Research Co.: Robin W. Dent, Senior Research Associate, for his assistance with interpretation of the statistical analysis and Dr. Milton M. Platt, Senior Director, who expertly handled contractual matters. The high-speed flex-testing apparatus, an adapted Ford Motor Company Pinto engine, was designed by James G. Donovan, based on a flexing method pioneered by author Dr. John Skelton, and was built at Albany International Research Co at AI's expense.

For their participation in the overall Finger Materials program, sincere appreciation also goes to the Landing Craft-Air Cushion Program Office (DTNSRDC Code 118) and the Air Cushion Vehicle operators who field tested experimental coated fabrics. These include the Amphibious Assault Landing Craft-Experimental Trials Unit (a detachment of DTNSRDC) in Panama City, Florida, for trials on the JEFF (B); the U.S. Army Mobility Equipment Research and Development Command in Fort Belvoir, Virginia, for trials on the Lighter Air Cushion Vehicle-30 ton payload; the Canadian Coast Guard in Montreal, Canada, for trials on the Voyager; and Hoverspeed, Ltd. in Dover, Kent, United Kingdom, for trials on the SRN4 Mk. 2. A special note of thanks goes to Mr. James J. Kelly, Office of Naval Technology, Washington, D.C., Dr. H. H. Vanderveldt of the Naval Sea Systems Command, Washington, D.C., and Dr. W. Denney Freeston of the Georgia Institute of Technology, Atlanta, Georgia, for their foresight and guidance throughout this project.

FOREWORD

The high speed and versatility of Air Cushion Vehicles (ACV) offer significant potential for military applications. However, in amphibious transit over land and water, the lower appendages, called fingers, are subjected to severe flexing and abrasion, shortening the life of the finger. As a result, craft performance is degraded and life-cycle costs increase. The objective of this exploratory development project was to develop enough information on fabric and coatings to guide development or selection of coated fabrics as finger materials for Navy air cushion craft.

Volume I, the first of three, described a comprehensive evaluation of coatings for finger materials for air cushion vehicles. The approach taken, in which materials were screened in preliminary dynamic tests in order to identify surviving candidates for further laboratory characterization, was a sensible and economical approach. In this work, the fabric was held constant and the coating was varied.

This volume, the second, describes the effect of fabric structure on the performance of finger materials. Here, the coating was held constant and the fabric was varied. A natural rubber/polybutadiene blend coating was common to both endeavors and served as a reference control tying both efforts together. The design and manufacture of a high-speed flex-testing apparatus using a Ford Motor Company Pinto engine was an economical innovative approach to achieve reciprocal motion and multi-test station capacity.

Volume III (to be published) describes the coated fabric as a finger material. Performance was measured in the laboratory on a unique dynamic testing facility called the "Drum Impactor" and in the field on operational air cushion vehicles. The information contained in Volumes I and II was used to define coated fabric constructions, which were subsequently manufactured and tested as detailed in Volume III.

The series of experimental fabrics was produced with the assistance of various other divisions of Albany International, including the Technical Fabrics Division, Auburn, ME, and North Monmouth, ME, (weaving, heat-setting) and Technical Fabrics Division, Buffalo, NY, (final rubber press coating). The Arkwright Finishing Plant, Fall River, MA, a division of United Merchants, was kind enough to allow use of their facilities for beam-scouring of fabrics.

INTRODUCTION

In the 1950's the technology was developed for putting into practice an idea that had been around for about a century--the idea of a vehicle that could travel over the land or sea supported above the surface by a continuously self-generated cushion of air.[1*] The first crossing of the English Channel by such a "surface effect vehicle" (SEV) was made in 1959 by the SRN1, a forerunner of the craft shown in Figure 1. The principal advantage of such vehicles is that the limiting effect of drag is overcome to such an extent that oversea speeds can approach 100 knots, whereas the top speed of more conventional surface ships is about 30 knots. The high speed and the potential for amphibious use of surface effect vehicles have far-reaching military implications: coastline troop and equipment dispersal may be accomplished more quickly and under far more hostile conditions of weather and terrain than with conventional landing craft; larger vehicles, perhaps in the 3000-ton range, could be used as ocean-going "mother ships."

Air cushion vehicles now operating in the English Channel, such as the 200-ton SRN4 built by British Hovercraft Corporation (see Figure 1), can carry 254 to 282 passengers and 30 to 37 cars. These vehicles are propelled by aircraft propellers and are supported on a cushion of air that is generated by high-speed fans; air is distributed to the area under the craft from a peripheral elastomeric ducting system called a "bag." Present-day craft maintain cushion pressures generally in the range of 30 to 100 psf. The cushion of lifting air is retained by a system of peripheral seals such as the "bag and finger" system of the SRN4 illustrated in Figure 2. The articulated nature of the flexible fingers allows the craft to traverse obstacles or waves with a minimum loss of air. Of the several different seal systems in current use, all involve flexible reinforced elastomeric panels in some form.

As the vehicle moves through the water, the tips of the skirt panels, particularly in the bow and stern regions, undergo a complicated combination of severe dynamic loading conditions: high-frequency, high-curvature flexing and impact. The magnitude and frequency of such potentially damaging cyclic loading

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*References are listed on page 77.

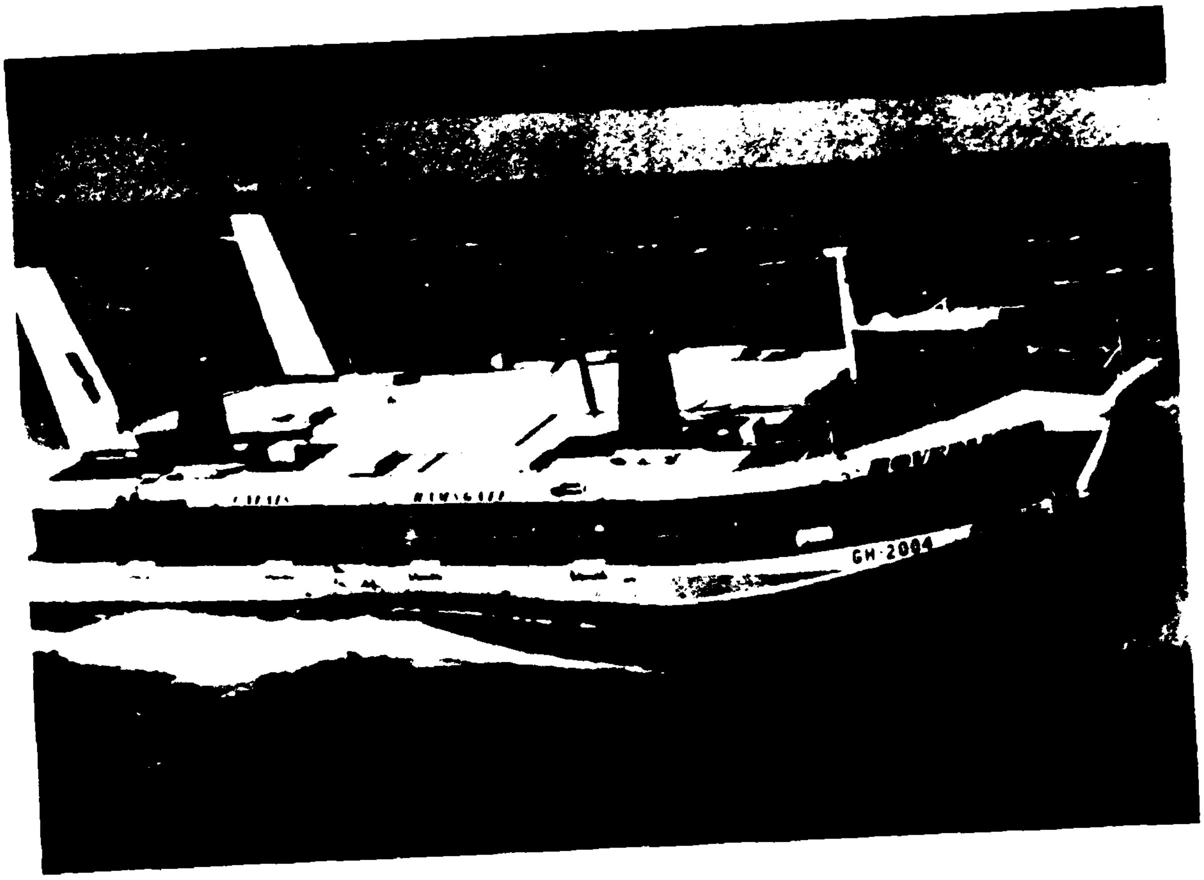


Figure 1 - Surface Effect Vehicle: SRN4 Hovercraft[1]

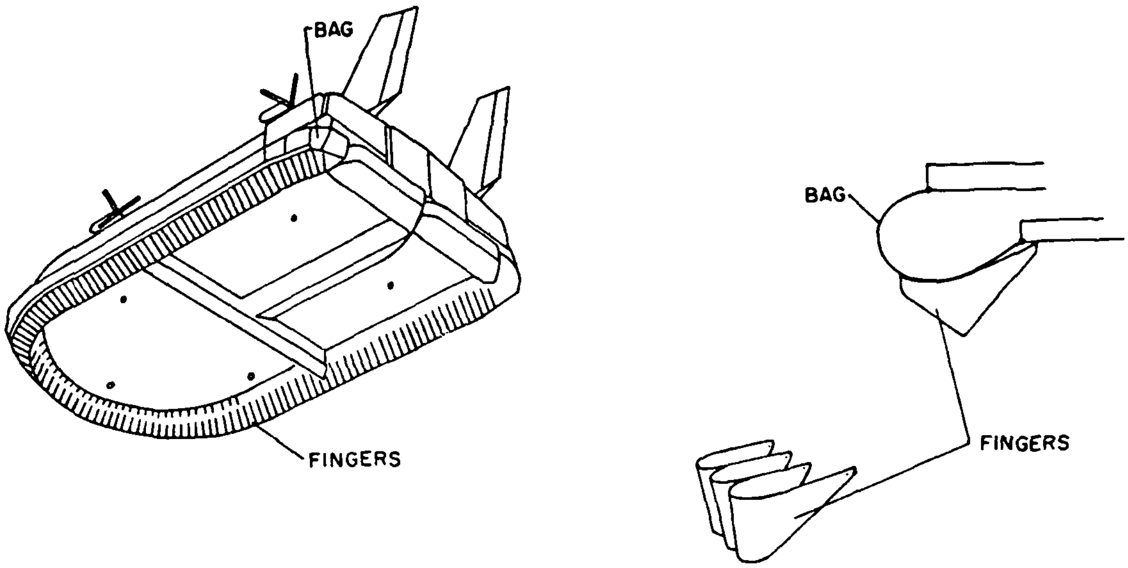


Figure 2 - Bag and Skirt Fingers: SRN4 Craft[1,3]

have been documented by Malakhoff and Davis:[2] depending on the forward speed of the craft and the air cushion pressure, average accelerations on the order of 300 g's with peak accelerations of 400 g's have been documented at frequencies near 200 Hz. In addition to such high-speed cyclic stressing, the skirt panels are subject to isolated, but possibly very damaging, abrasion from impact with floating objects and debris.

The principal modes of failure observed in actual skirt panels include delamination, abrasion, and tearing. Delamination, or separation of the elastomeric coating from the woven reinforcing substrate, sometimes preceded by flex-cracking of the elastomeric layer, is thought to represent an early stage of failure. Unsupported, the elastomer can be rapidly torn away from the substrate and exposed to the deleterious effects of seawater. When the work described here was originally conceived, it was believed that delamination was principally flex-engendered, as evidenced by flex-cracking of the elastomer. It now appears, however, from work ongoing at the David Taylor Naval Ship Research and Development Center (DTNSRDC), that for at least some skirt material designs, high-speed impact is a more important factor in initiating delamination than is flex fatigue. The energy transmitted during impact seems to be enough in many cases to disrupt the adhesive bond between substrate and elastomer. Protection against abrasive damage that is not the result of previous delamination depends mainly on the thickness of the elastomeric layer. Resistance to tearing, which occurs principally at the skirt attachment points, is controlled by the tensile properties of the fabric reinforcement.

Although little is known in detail about the actual failure sequence and processes, clearly the major shortcoming of SEV's is the short lifetime in use of their skirt systems. The average lifespan of the bags on the SRN4 is 2000 hours; of bow fingers, 500 hours; and of stern fingers, 200 hours.[3] These short lifetimes of the seal/skirt system severely limit the military potential and commercial practicality of surface effect vehicles.

With DTNSRDC, the Albany International Research Co. has attempted to study the effects of several fabric construction variables on the <u>lifetime in flex</u> of fabric/elastomer composite materials suitable for use in skirts. We have taken as our mandate the opinion expressed by the Committee on Skirts and Seals for Surface Effect Vehicles, National Materials Advisory Board, National Research

Council[3]: "An extensive, systematic study of the effects of fabric structure on skirt performance should be conducted." Although high-speed impact may be the loading condition that begins delamination in some currently used skirt materials that are poorly bound together, for materials having a stronger adhesive bond, there is still clear evidence that flex-cracking is a principal failure mode. As newer and better adhesive systems are developed, the effects of impact may become secondary and flex-fatigue may become the dominant mode of failure of fabric-reinforced skirt materials.

EXPERIMENTAL FABRIC DESIGN AND PRODUCTION

To investigate the effect of the construction of the woven substrate on the flex-fatigue behavior of elastomer-coated fabrics, several fabric construction parameters were varied while the following factors were kept constant:

- fiber material - high tenacity nylon 6,6
- fabric tensile strength - 1200 lb/in. in the two principal directions
- elastomeric coating -
  - composition - natural rubber/polybutadiene blend ECB-502
  - tie coat - Neoprene GNA blend ECB-341 adhesive with isocyanate curing agent
  - amount - 0.030 in. calendered sheet applied to each side
  - method of application - platen press, 300°F, 30 min, 440 psi.

See Appendixes A and B for more details concerning the coating formulations and coating methods, respectively.

The fabric construction variables studied are summarized in Table 1. They were fiber denier, yarn denier, yarn twist, fabric float length, weave pattern, and crimp level--six construction variables, one at three levels, five at two levels. Four of these variables--fiber denier, yarn denier, yarn twist and weave pattern--are specified by absolute values: 2, 6, or 12 denier per filament (dpf); 5040 or 10,080 nominal yarn denier; 5° or 25° surface helix angle, and either a twill- or basket-weave pattern. The two remaining factors, however, are specified at relative levels: 1 x 1 or 3 x 3 for float length, which in actual length units depends on the denier of the yarns crossed in a particular structure and on the count; and low and high crimp level, for which the absolute value depends on both yarn denier and float length.

TABLE 1 - FABRIC CONSTRUCTION VARIABLES

FIBER:	Denier	Type	
	6	DuPont 728 (714)	
	6, 12	DuPont 704	
	2, 6	Monsanto CO2	
YARN:	Denier	Twist	
	5,040	Low - 0.8 tpi (5^{o}) High - 4.1 tpi (25^{o})	
	10,080	Low - 0.5 tpi (5^{o}) High - 3.1 tpi (25^{o})	
FABRIC:	Float Length	Weave Pattern	Yarn Crimp
	1 x 1	Twill	Low
	3 x 3	Basket	High
Full Factorial Experiment - $2^5 3^1$ = 96 Combinations 48 Fabrics			

A full factorial experiment involving each of the fabric construction variables at each level would require the manufacture of $2^5 3^1$ = 96 fabric types, a number which could be halved if the fabric were woven so that the low crimp yarns lay only in the warp direction, and the high crimp yarns in the filling direction.

It was not possible to obtain nylon yarns of the same type in each of the fiber deniers of interest. DuPont Type 728 was of principal interest because of its high tenacity, nearly 9 grams per denier (gpd). Since this material was available only in 6 dpf, two other yarn types were also included in the experiment; these were DuPont Type 704, available in both 6 and 12 dpf, and Monsanto CO2, available in both 2 and 6 dpf. With this selection, 6 dpf fibers of three different types could be compared as could two different deniers of each of two fiber types. DuPont Type 714 in 10,080 denier had to be substituted for Type 728, to which it is very similar; Type 728 was unavailable at the time in this denier. Typical stress-strain diagrams for each of these materials are given in Figure 3 and average tensile properties are summarized in Table 2. The yarn construction is described in both the Figure and the Table by a string of descriptors as follows: denier, number of filaments, twist, and type.

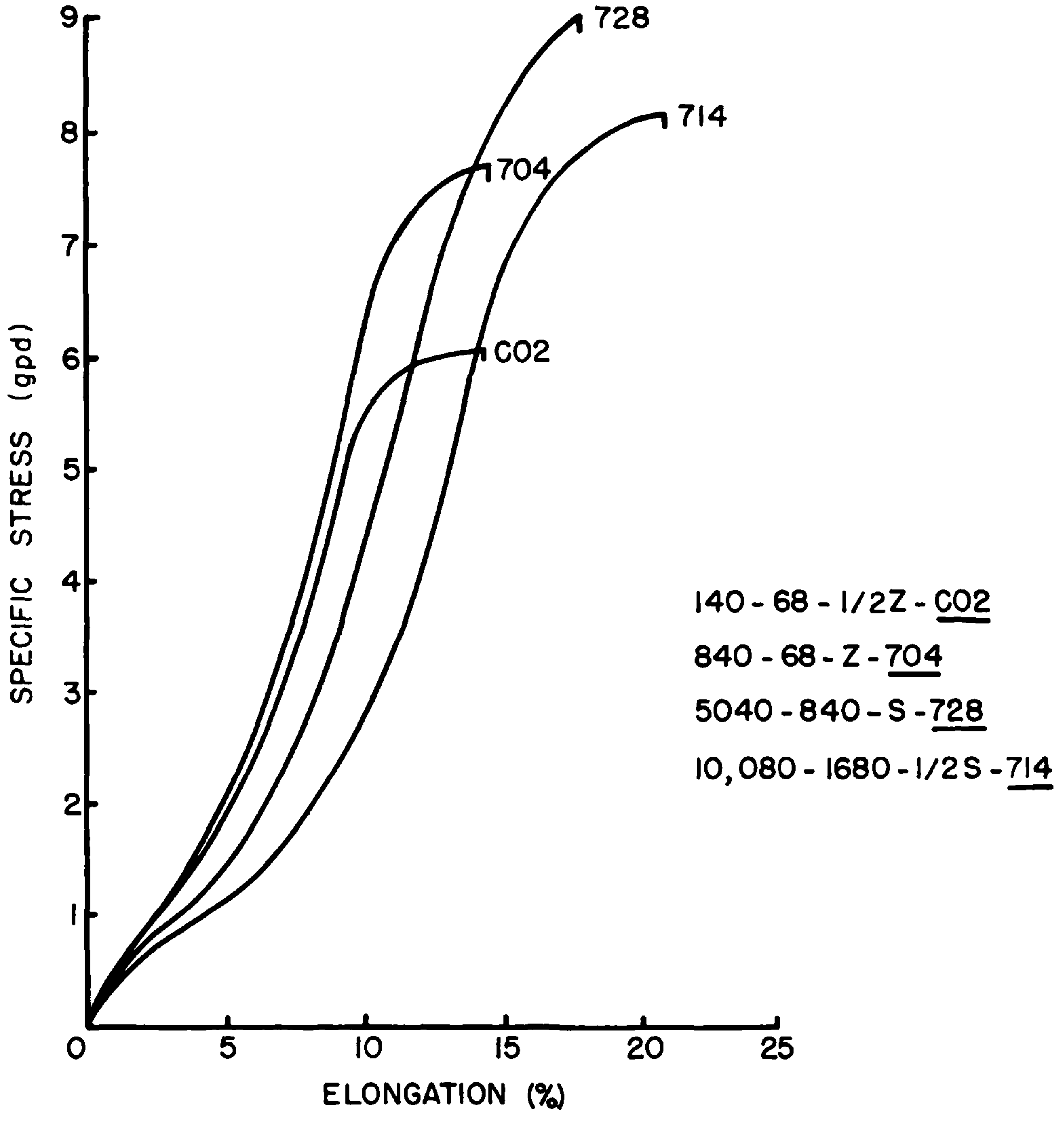


Figure 3 - Stress-Strain Diagrams of Various Nylon Yarn Types
(See Text for Definition of Yarn Nomenclature)

TABLE 2 - AVERAGE TENSILE PROPERTIES OF SINGLE AND PLIED YARNS

Yarn Construction*	Denier	Initial Modulus (gpd)	Rupture Elongation (%)	Rupture Load (lb)	Translational Efficiency (%)	Tenacity (gpd)
5040-840-S-728 (DuPont)	5,140	45	16	99.2	--	8.8
1/(5040-840-S-728)/1.0S	5,340	30	20	99.6	100	8.5
1/(5040-840-S-728)/3.0S	5,680	21	25	107.4	108	8.6
1/(10,080-1680-0-714)/0.5S (DuPont)	10,640	40	20	192	--	8.2
1/(10,080-1680-0-714)/1.0S	10,650	37	20	197	103	8.4
1/(10,080-1680-0-714)/3.0S	11,400	22	24	185	96	7.4
840-68-Z-704 (DuPont)	865	51	15	14.7	--	7.7
6/(840-68-Z-704)/0.5Z	5,288	29	19	88.2	100	7.6
12(840-68-Z-704)/0.5S	10,730	29	20	182	103	7.7
12/(840-68-Z-704)/3.0S	11,590	19	25	183	104	7.2
140-68-1/2Z-CO2 (Monsanto)	143	47	14	1.9	--	6.1
36/(140-68-1/2Z-CO2)/0.5Z	5,560	25	29	75	109	6.1
72/(140-68-1/2Z-CO2)/0.5Z	10,470	30	22	141	103	6.1
72/(140-68-1/2Z-CO2)/3.0Z	11,640	14	31	139	101	5.4
630-102-Z-704B (DuPont)	635	50	14	11.0	--	7.8
8/(630-102-Z-704)/0.5Z	5,280	30	18	85	97	7.3
420-68-1Z-CO2 (Monsanto)	420	48	16	6.6	--	7.1
12/(420-68-1Z-CO2)/0.5Z	5,390	30	23	74	93	6.2

*See text for definition of nomenclature.

The initial modulus of the yarns as supplied with little or no twist ranged from a low of 40 gpd for DuPont Type 714, 6 dpf, to a high of 51 gpd for DuPont Type 704, 12 dpf. Yarn tenacities ranged from 8.8 gpd for DuPont Type 728, 6 dpf, to 6.1 gpd for 2 dpf, Monsanto Type CO2. The close similarities in the stress-strain behavior of the various materials in the early stages of stressing were thought to be more important in the flexing experiments than differences in ultimate strength. The absolute strengths and tenacities of the yarns after plying and twisting are also given in Table 2.

The yarn deniers chosen for the experiment were determined by the fabric design criterion of 1200 pounds per lineal inch. The number of fabric ends per inch necessary to achieve this level of tensile strength with 8 gpd yarns and

various yarn deniers is compared in Table 3 with the maximum number of ends weavable in a square, plain-woven fabric.[4] As seen from the table, only yarn deniers above 5040 are suitable for such constructions. Fabrics were constructed from nominally 5040 and 10,080 denier yarns only since it was thought that fabric woven from 15,000 denier yarns would be too sleazy and difficult to handle.

TABLE 3 - DETERMINATION OF YARN DENIER FROM FABRIC STRENGTH CRITERION OF 1,200 POUNDS PER LINEAL INCH

Criterion:	Number of Fabric Ends per Inch with Yarn Denier (multiples of 840) of--					
	2,520	3,360	5,040	7,560	10,080	15,120
To achieve 1,200 lb/in. (at 8 gpd)	27	20	14	9	7	5
Maximum weavable in square plain weave	20	18	14	12	10	8

Two levels of yarn twist were adopted: low (a 5° yarn surface helix angle) and high (a 25° yarn surface helix angle). The low levels were to be achieved by 0.8 twists per inch (tpi) in the 5040 denier yarn and by 0.5 tpi in the 10,080 denier yarn. Similarly, 4.1 tpi would represent the high level of twist for the lower denier yarn whereas 3.1 tpi would be suitable for the higher denier yarn.

Fabrics were to be either plain woven or 3 x 3 twill or basket weaves. Emphasis was placed on the twill construction with only a few basket weaves to be produced. Yarn crimp was to be controlled during fabric production and subsequent finishing by the application of tension in the warp direction so that most of the crimp would be in the filling direction yarns.

Six fabric warps were produced as described in Table 4. From these six warps more than 40 different fabric structures were woven in approximately 10 yard lengths, each 36 in. wide, by varying the weave pattern and filling yarn twist as the fabrics were woven out. (These included some basket weaves, and a few 2 x 2 constructions, as well as some medium twist level constructions, many of which were not subsequently evaluated because of budgetary limitations.) The various fabrics were produced in general by weaving with the same type of filling yarn as used in the warp except that the twist level of the filling yarn was varied. However, four plain weave fabrics were woven from Warp I in which the filling yarns

were constructed from different yarn types and fiber deniers than the warp yarn. The detailed construction of each of the fabrics produced is given in Table 5 where those constructions subsequently evaluated for flex behavior are also noted. The large effect of yarn twist on the extent of fabric openness is illustrated in Figures 4a and 4b for plain-woven and 3 x 3 twill constructions, respectively.

TABLE 4 - EXPERIMENTAL FABRIC WARP CONSTRUCTION

Warp* No.	Fiber Denier	Yarn Denier	Ends/ Inch	Warp Yarn Twist Level
I	6	5,040	14	Low
III	6	10,080	7	Low
IV	12	5,040	14	High
V	12	10,080	7	Low
VI	2	5,040	14	Low
VII	2	10,080	7	High

*Construction was generally the same in both warp and filling directions except for yarn crimp level and filling yarn twist level.

Finishing of the various fabrics included scouring, *heat-setting at* 350°F, application of the adhesive tie coat, and final platen pressing of the rubber layers onto the substrate at 300°F. Additional details describing these finishing procedures and where they were performed may be found in Appendix B.

The properties of the resulting rubber-coated fabrics are summarized in Table 6. The tensile and tearing strengths of only a few selected 10,080-denier constructions were measured after coating because of budgetary restrictions. Test results for individual fabrics are given in Appendix A, and test procedures are given in Appendix B. In general, the fabrics were of good appearance after coating. Although layers of rubber of initially controlled thickness were applied to each construction, some variations in final thickness ensued mostly because of variations in the thickness of the fabric substrate. The amount of coating material applied was barely enough in some cases to fill the fabric structure, particularly for those thicker fabrics consisting of high twist, high denier yarns. Cross sections of many of the coated fabrics produced are shown in Figures 5 through 8.

TABLE 5 - DETAILS OF EXPERIMENTAL FABRIC CONSTRUCTION

Warp No.	Warp Yarn Twist Level	Fiber Denier	Warp and Filling Construction Nominal Yarn Denier	Yarn Count (yarns/in.)	Weave Pattern	Filling Yarn Twist Level
I	low	6 (Type 728)	5,040	14 x 14	plain	low* medium* high*
					2 x 2 twill	low high
					2 x 2 basket	low high
					3 x 3 twill	low* medium high*
					3 x 3 basket	high*
In addition, Warp I contained the following four fabric constructions designed to provide a basis of comparison between yarn types:						
Filling Direction Fiber Denier and Type		6 (Type 704)	5,040	14 x 14	plain	low*
		12 (Type 704)	5,040	14 x 14	plain	low*
		2 (Type C02)	5,040	14 x 14	plain	low*
		6 (Type C02)	5,040	14 x 14	plain	low*
III	low	6 (Type 714)	10,080	7 x 7	plain	low* medium high*
					2 x 2 twill	low* high
					2 x 2 basket	low high
					3 x 3 twill	low* medium high*
					3 x 3 basket	low* high*
IV	high	12 (Type 704)	5,040	14 x 14	plain	low* high*
					3 x 3 twill	low* high*
V	low	12 (Type 704)	10,080	7 x 7	plain	low* high*
					3 x 3 twill	low* high*
					3 x 3 basket	low*
VI	low	2 (Type C02)	5,040	14 x 14	plain	low* high*
					3 x 3 twill	low* high*
VII	high	2 (Type C02)	10,080	7 x 7	plain	low* high*
					2 x 2 twill	high
					3 x 3 twill	low* high*

*Flex fatigue measurements made.

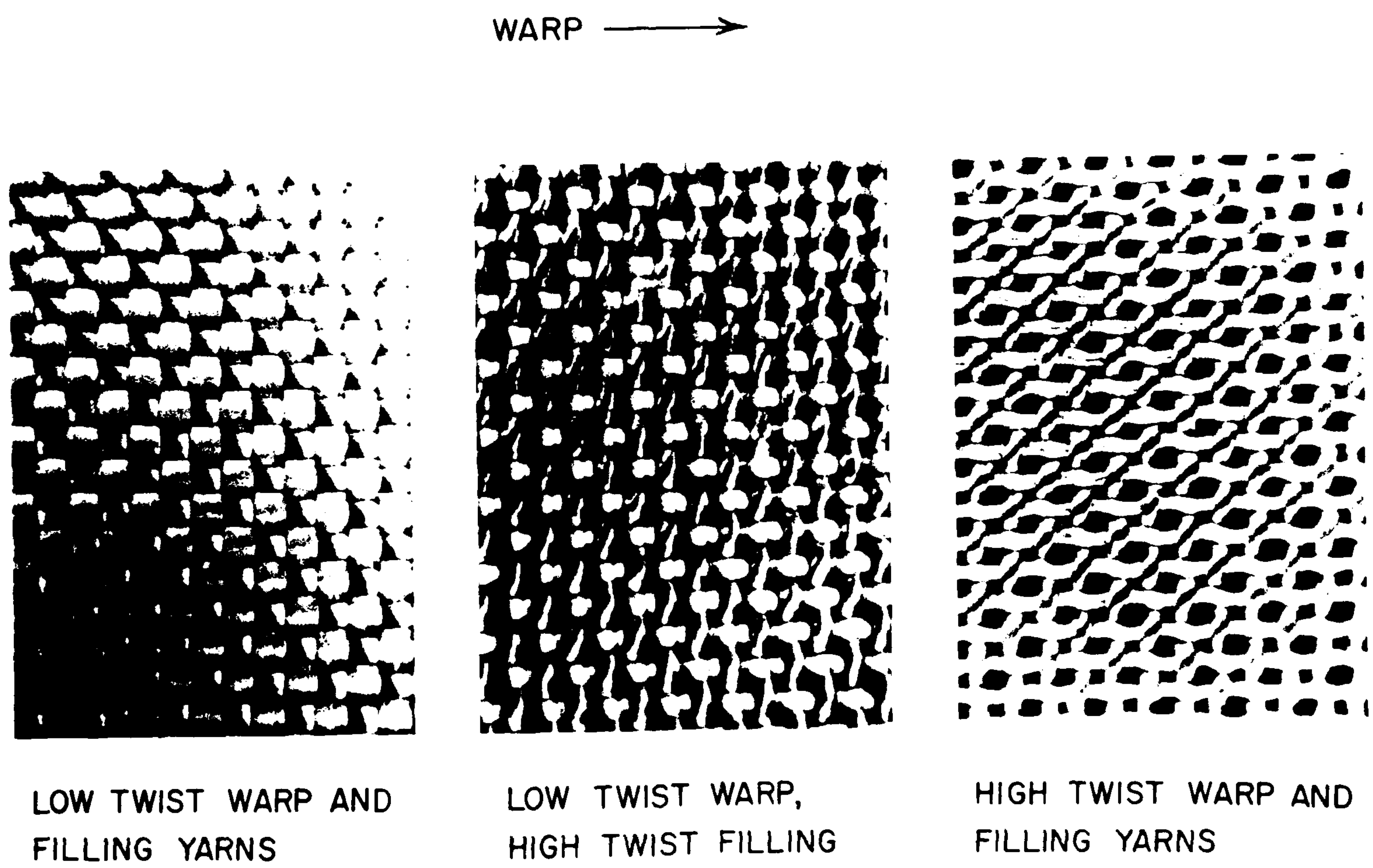
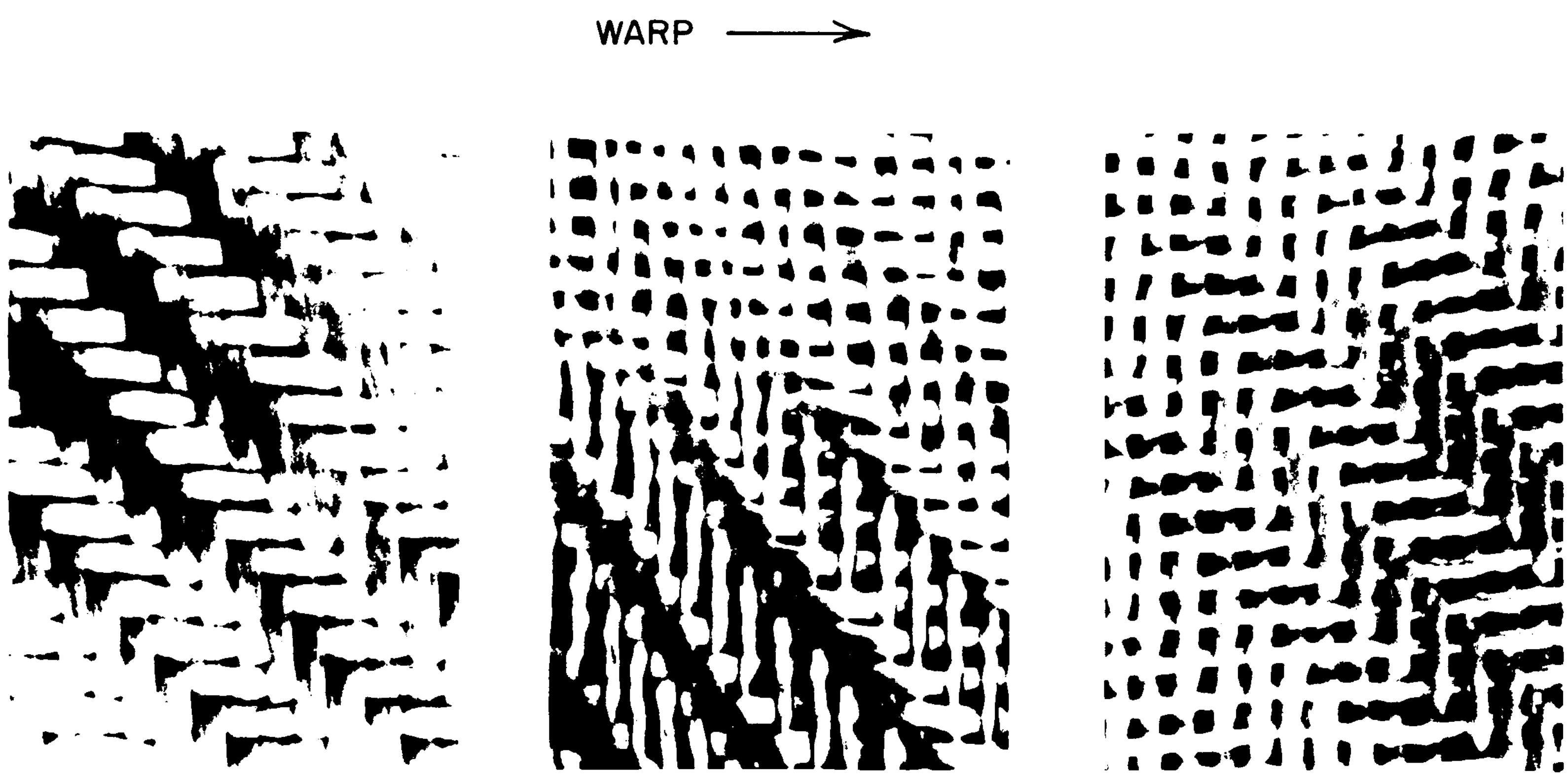


Figure 4a - Effect of Yarn Twist on Fabric Openness: 10,080 Denier, Plain Weave



LOW TWIST WARP AND FILLING YARNS

LOW TWIST WARP, HIGH TWIST FILLING

HIGH TWIST WARP AND FILLING YARNS

Figure 4b - Effect of Yarn Twist on Fabric Openness: 3 x 3 Twill Weave

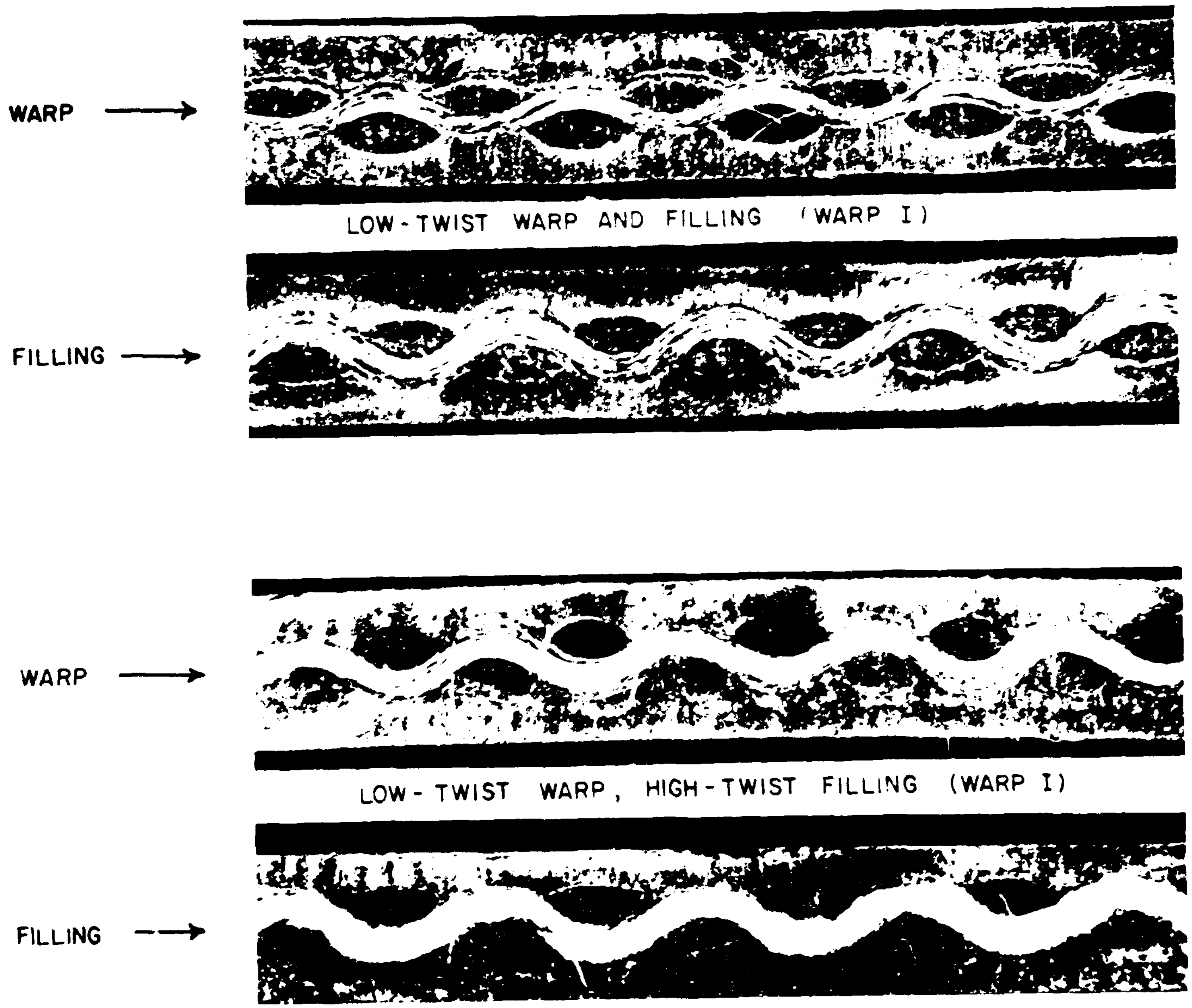


Figure 5a - Cross-Sections of Rubber-Coated, 5040 Denier, Plain-Weave Fabrics: Low-Twist Warp

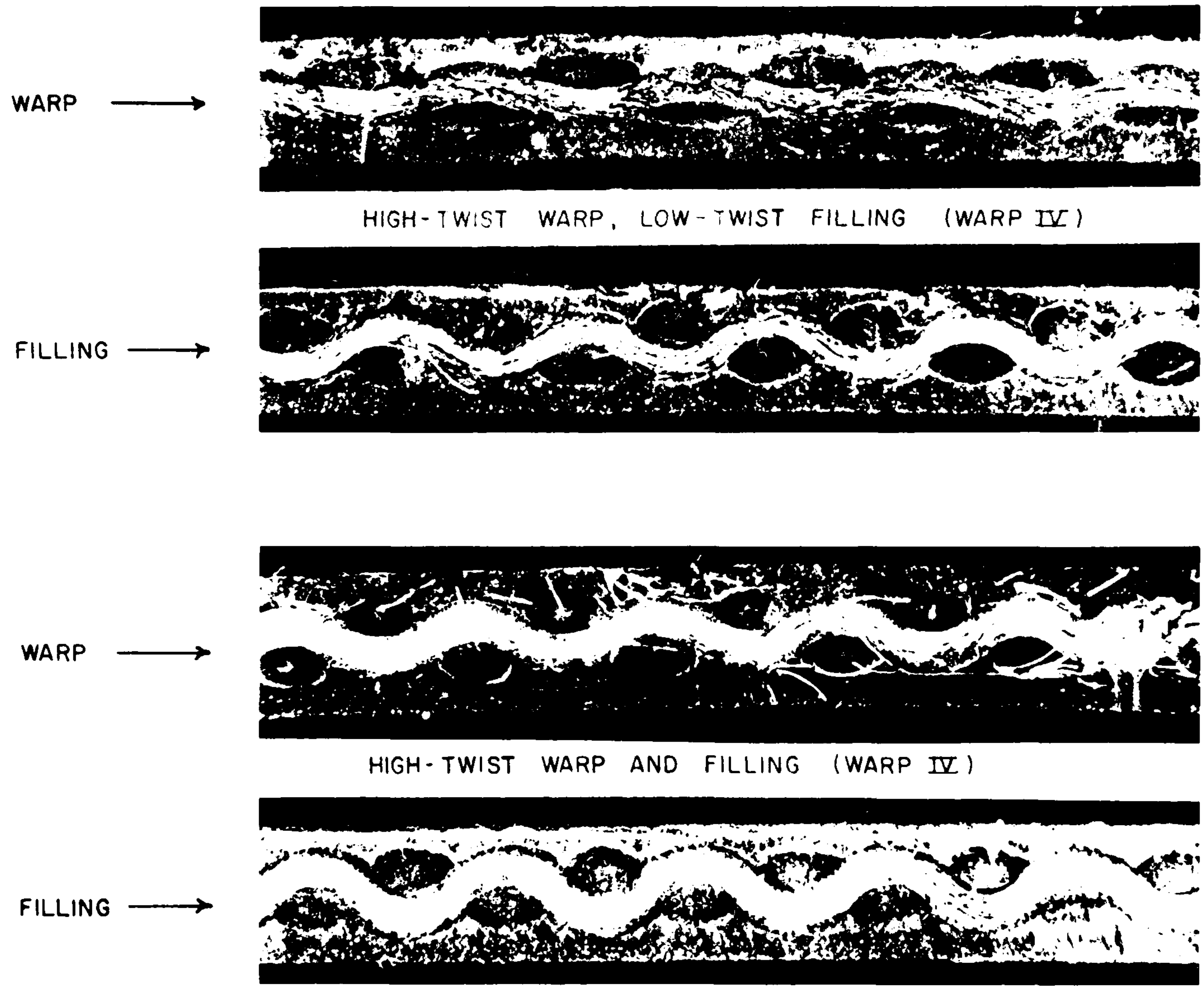


Figure 5b - Cross-Sections of Rubber-Coated, 5040 Denier, Plain-Weave Fabrics: High-Twist Warp

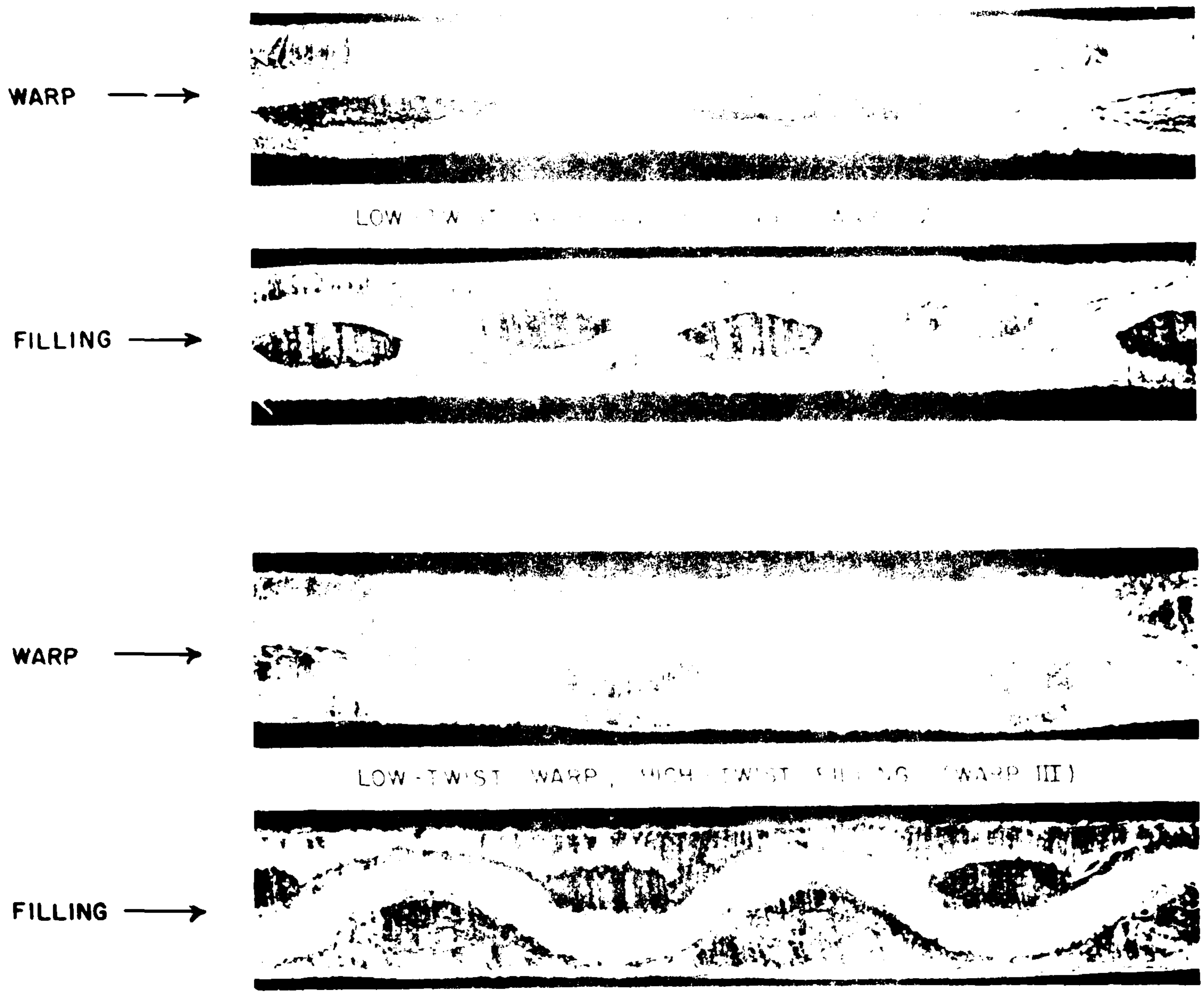


Figure 6.1 - Cross-Se

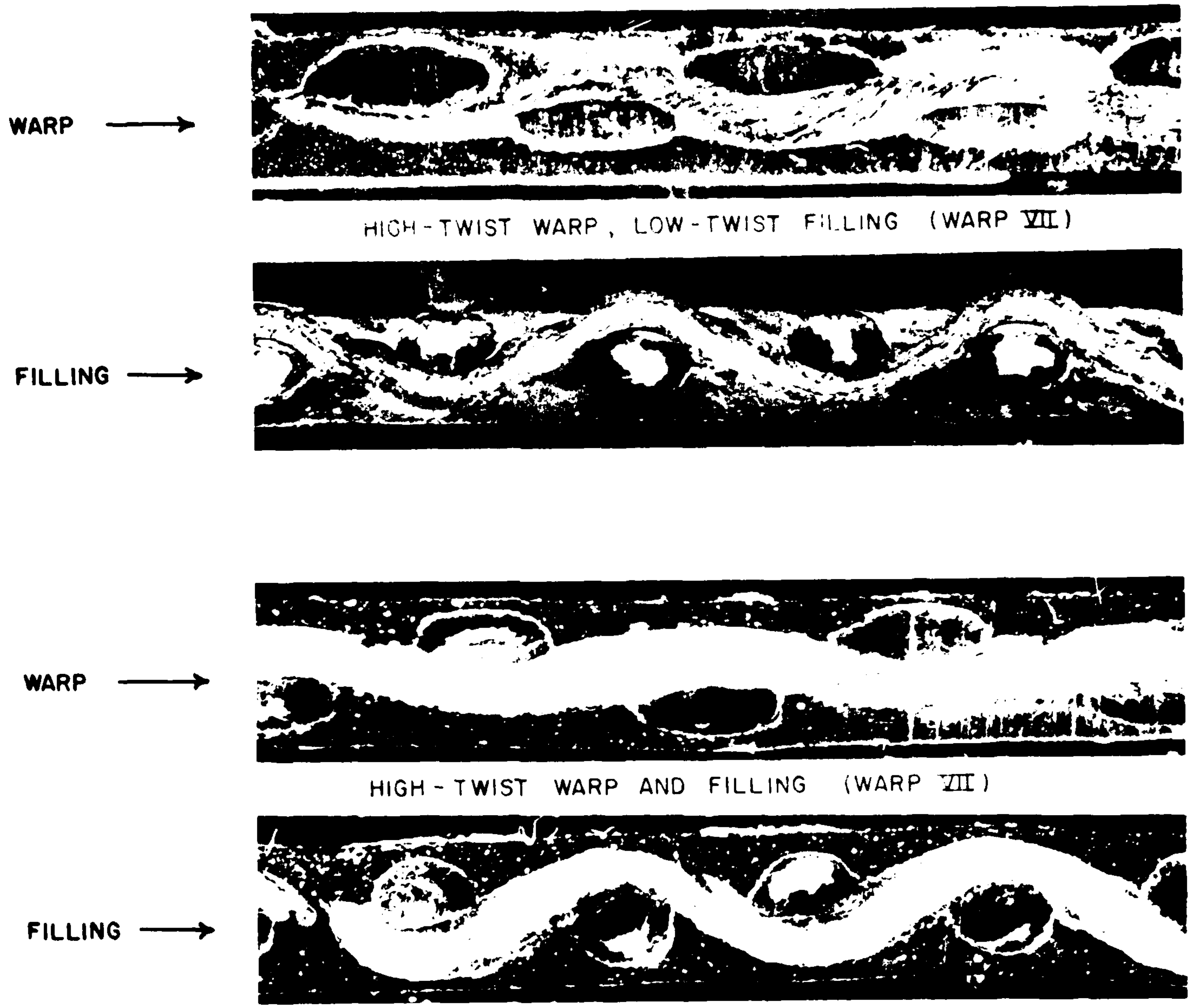


Figure 6b - Cross-Sections of Rubber-Coated, 10,080 Denier, Plain-Weave Fabrics: High-Twist Warp

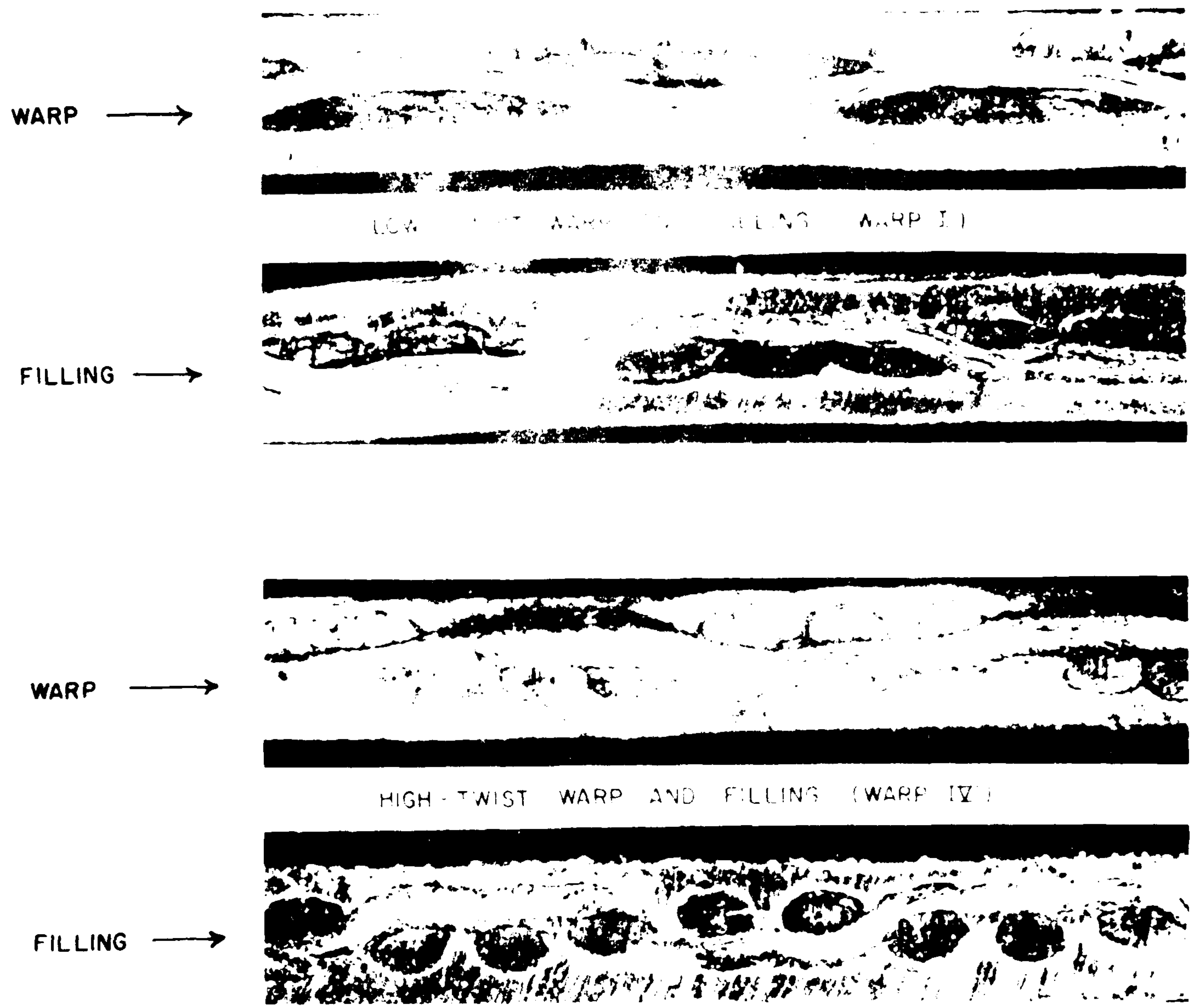

WARP
FILLING
WARP
HIGH-TWIST WARP AND FILLING (WARP IV)
FILLING

Figure 7 – Cro...

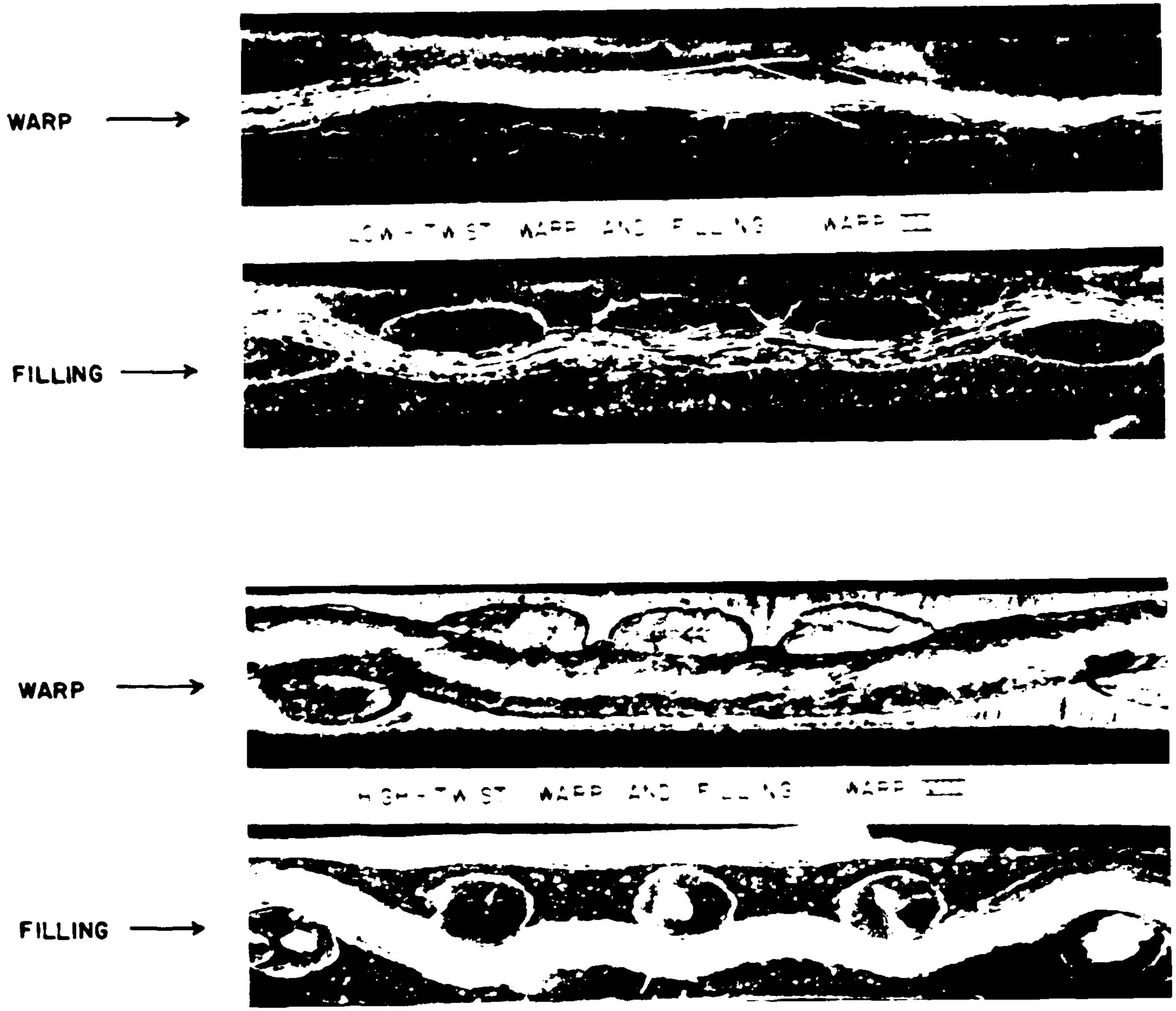


Figure 8 - Cross-Sections of Rubber-Coated, 10,080 Denier, 3 x 3 Twill Fabrics

TABLE 6 - COMPOSITE FABRIC PROPERTIES

WEIGHT:	
Substrate	20 to 27 oz/yd^2
Coated Fabric	70 to 80 oz/yd^2
THICKNESS:	
Substrate	0.05 to 0.09 in.
Coated Fabric	0.09 to 0.11 in.
STRENGTH:	
Tensile	900 to 1300 lb/in.
Tear	500 to 1000 lb/in.

The sections of Figures 5 through 8 illustrate the various levels of success in attaining straight warp yarns and highly crimped filling yarns. In the plain-woven, 5040 denier fabrics (Figures 5a and 5b) yarn crimp is nearly balanced. Among the 10,080 denier plain-woven constructions (Figures 6a and 6b) a greater difference in crimp level between warp and filling yarns can be seen. In the longer float fabrics (Figures 7 and 8), the warp tends also to lie straighter than the filling. The high tensions applied in the warp direction were obviously insufficient in some cases to overcome the high transverse pressures in the press, which tend to equalize yarn crimp.

The fabric cross sections of Figures 5 through 8 illustrate another important difference among the finished fabrics, namely the variation in thickness of the rubber covering over the fabric knuckles. In fabrics woven from low denier, low twist yarns the minimum thickness of the covering layer is much greater than the minimum thickness in the high denier, high twist fabrics. Compare Figures 5a and 6b.

Since the variation in twist of the two sets of yarns in the fabric dramatically affects the extent of openness of the resulting fabric structure, as illustrated in Figures 4a and 4b, fabrics containing high-twist yarns in both warp and filling directions present the greatest opportunity for rubber strike-through or bridging of the coating material. This is a potentially important feature for producing highly effective coating "adhesion" strengths.

FLEX TESTING APPARATUS AND METHODS

To determine the relative performance of the various fabric constructions during flexing, a new flex tester, shown in Figure 9, was designed and built. The tester, a modified four-cylinder automobile engine, imposes a high-curvature rolling bend on 1.25 in. wide fabric strips inserted in special fixtures attached to the pistons. The high-speed reciprocating motion is driven by an electric motor. Each of the four pistons is equipped to hold four separate test specimens, each attached at one end to a stationary center post and at the other to a movable platform connected to the piston, as shown in Figure 10. The specimens are subjected to the rolling high-curvature deformation illustrated in Figure 11 and described more fully by Skelton[5]; the engine block is water-cooled to keep temperature uniform in all the specimens. The essence of the imposed deformation is that each element in the 2.4-in. central portion of the strip, which measures 5.0 in. in total length, undergoes a high-frequency cycle of curvature from no curvature to maximum curvature and back to no curvature in one cycle of reciprocating motion. Minimum radius of curvature, i.e., maximum curvature, undergone by each element is given by the expression[5,6]

$$r_{min} = (D-t)/2.4 \cong 0.17 \text{ in.}$$

where D, the distance between parallel supports, was set at 0.5 in. and t is the fabric thickness. Mean radius of curvature for the 0.5-in. spacing is given by:

$$\bar{r} = (D-t)/1.4 \cong 0.28 \text{ in.}$$

The length L of fabric being flexed through each cycle is expressed by:

$$L = 2.2(D-t) + \frac{3.1}{2} = 2.4 \text{ in.}$$

where 3.1 in. represents the length of the piston stroke.

The tester is capable of cyclic frequencies to 18 Hz. All of our testing was done at a frequency of 15 Hz, or 900 rpm, in air at room temperature.

A standard skirt material produced by the Goodyear Aerospace Corp. was used to prove the tester. This fabric is similar in weight, thickness and strength to the experimental fabrics produced as part of our investigation; details of its

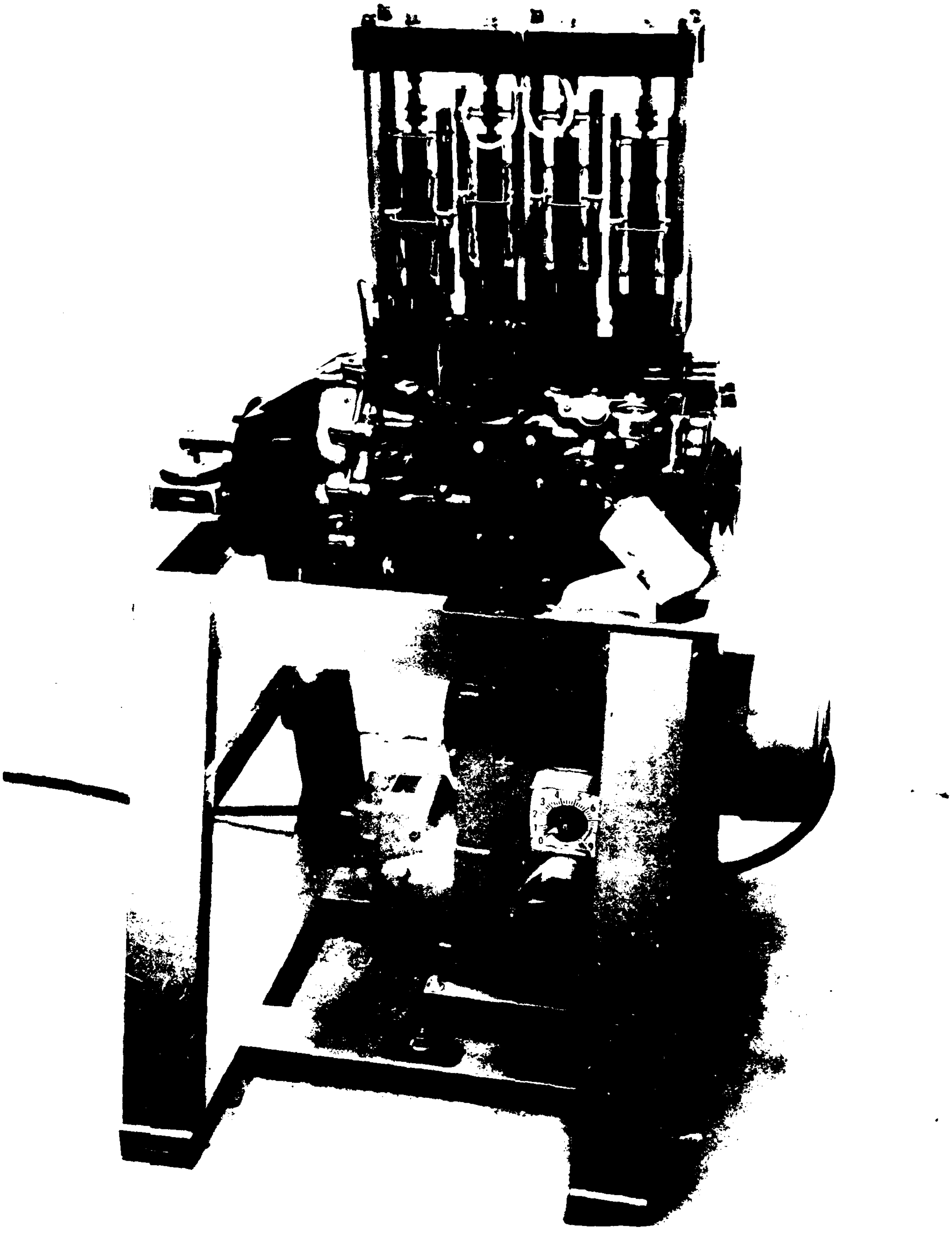


Figure 9 - Flex-Testing Apparatus

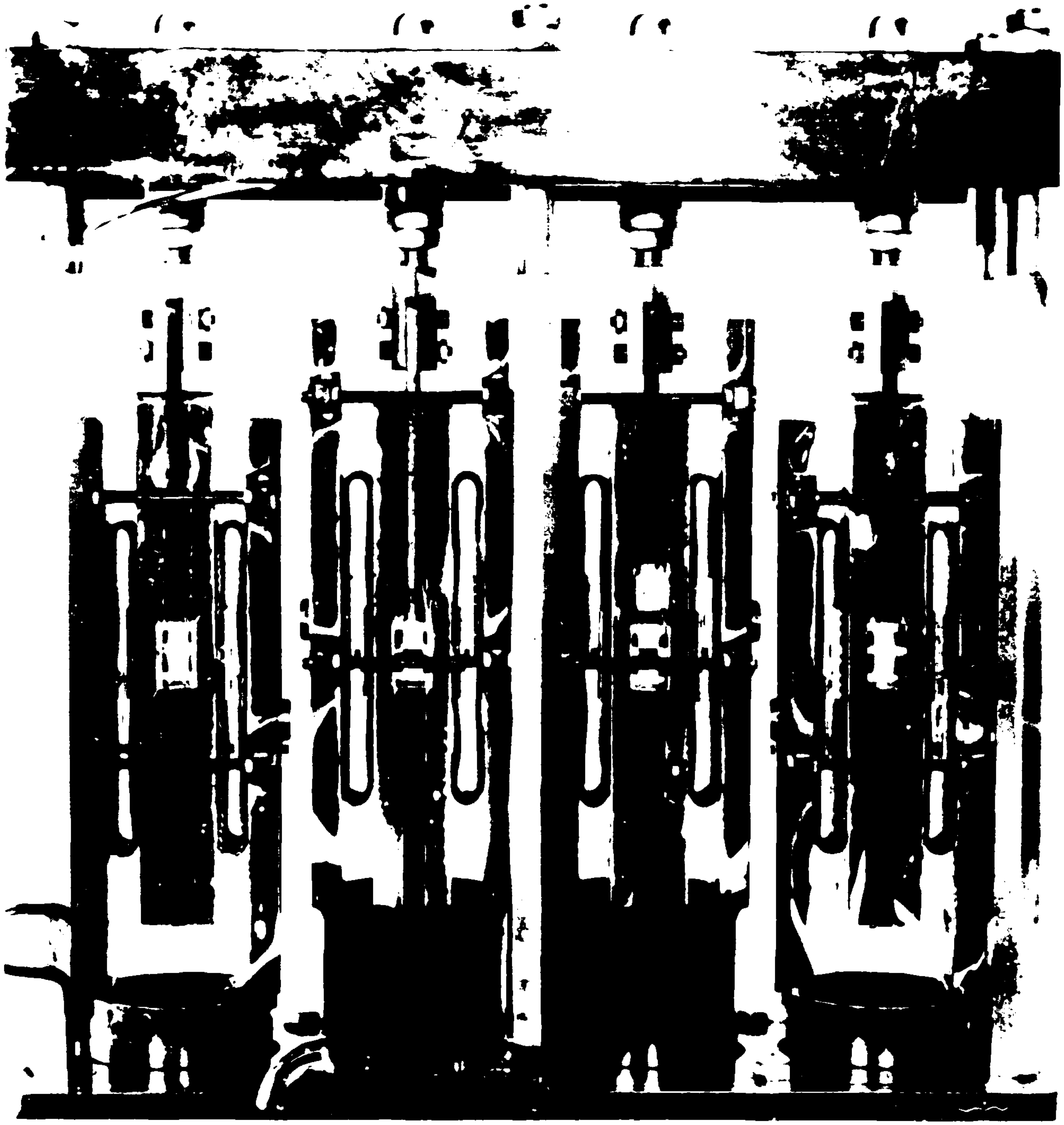


Figure 10 - Specimens in Position in Flex-Testing Apparatus

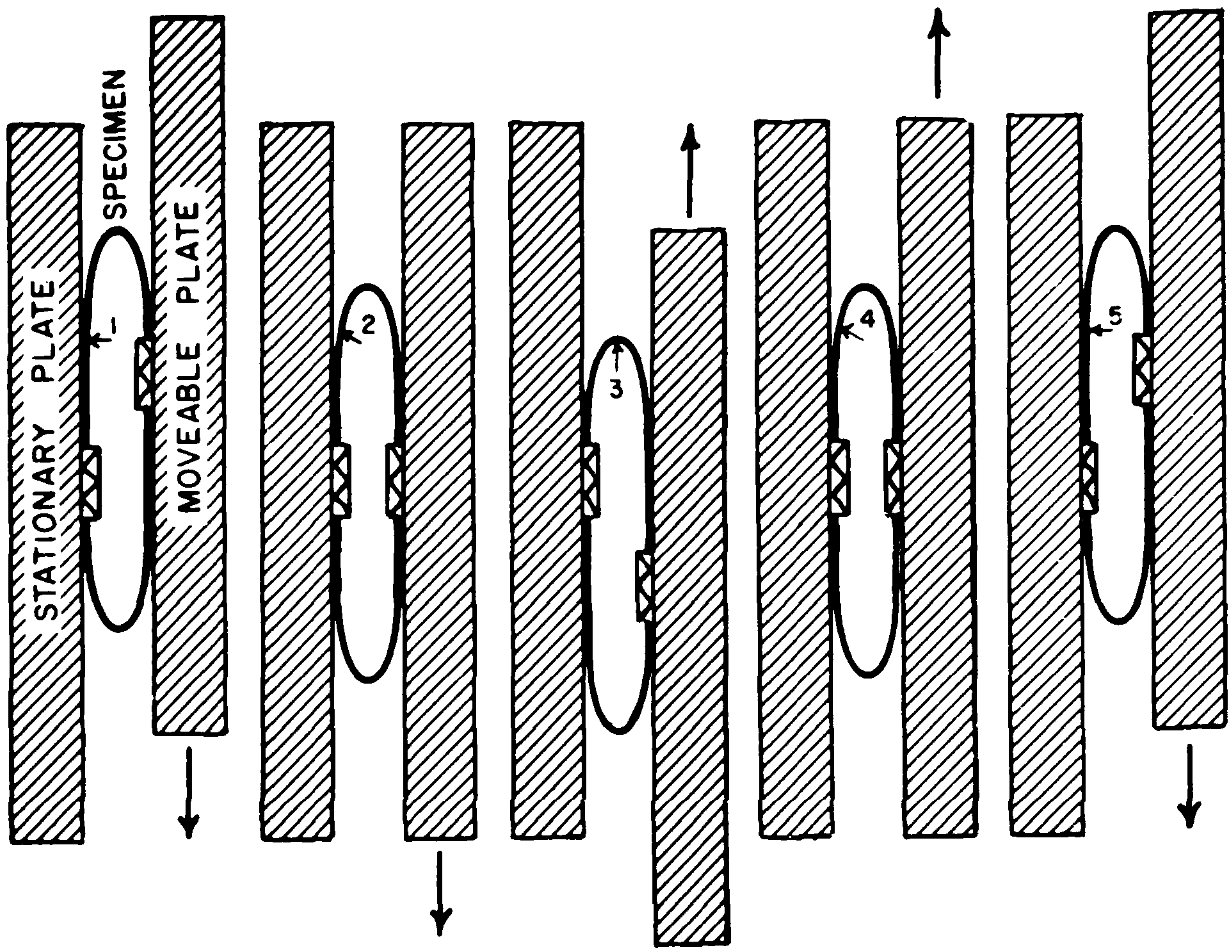


Figure 11 - Cycle of Curvature for Specimen in Flex-Testing Apparatus: For Element at Arrow, Positions 1 to 3 - 0 to Maximum, Positions 3 to 5 - Maximum back to 0

construction are given in Table 7. With fine-wire thermocouples inserted into several specimens of this fabric it was possible to monitor the equilibrium temperature of the fabric specimen, generally achieved within 5 min, over a range of cyclic frequencies up to 17.5 Hz. These temperatures are plotted in Figure 12 as a function of cyclic frequency. At the test frequency of 15 Hz an increase in internal temperature of approximately 40°C may be expected in undamaged fabric of this type.

TABLE 7 - CONSTRUCTION OF GOODYEAR FABRIC XA28A504-2A, THE FABRIC USED TO PROVE TESTER

Fabric Substrate Construction:	6 dpf nylon 4/2/840/12S/7Z 10 x 10 plain weave 27 oz/yd^2
Fabric Weight:	82 oz/yd^2
Fabric Thickness:	0.110 in.
Fabric Tensile Strength:	1200 lb/in. nominal

Each of the four stations of the flex tester is equipped with a dynamic force transducer, which can be used to monitor the force required to perform the reciprocating motion on each set of four specimens. This force, as described by Skelton[5], is proportional to the bending hysteresis, or frictional work lost by the fabric during the cycle of high-curvature deformation. Since this work loss is the result of frictional energy dissipation, principally in the form of heat, it was thought that its continual measurement might be used to indicate the onset of flex fatigue. Although the bending hysteresis loss monitored over several million cycles of flex of the Goodyear fabric did increase at the initial appearance of flex cracks, no promising indicator of the onset of failure was observed in the bending hysteresis loss values for several fabrics in the experimental series. (Typical curves of bending hysteresis loss with continued cycling for the Goodyear fabric and for the experimental fabrics are given in Appendix B.)

With each of the 16 positions on the flex-tester filled with the standard Goodyear fabric XA28A504-2A, the number of cycles to first failure was documented by visual inspection of each specimen. The results, listed in Table 8, illustrate the close agreement between the average value of the group of four specimens at

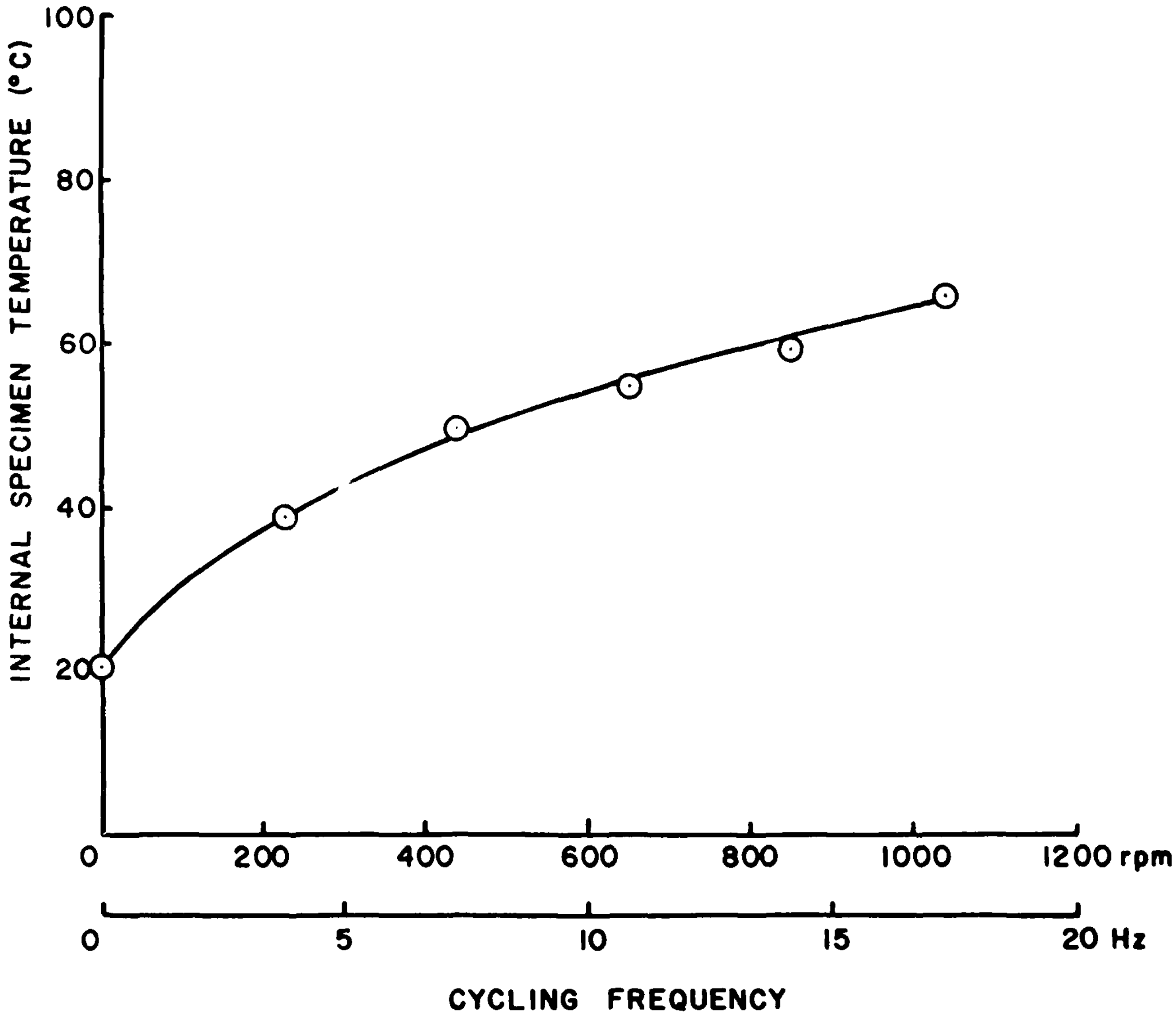


Figure 12 - Internal Temperature of Typical Rubber/Fabric Specimen During Flex Cycling

each test station with the overall average for all sixteen specimens. They also show the wide range of values obtained, leading to a coefficient of variation in the test data of approximately 50%. Such large variations are common in fatigue data.

TABLE 8 - NUMBER OF CYCLES TO FIRST EVIDENCE OF FLEX CRACKING IN GOODYEAR FABRIC XA28A504-2A

Test Station	Initial Flex Cracking (millions of cycles)		Average (millions of cycles)
1	3.9, 1.5, 1.9, 2.7		2.5
2	2.2, 5.2, 1.5, 1.5		2.6
3	1.9, 2.4, 2.2, 3.9		2.6
4	0.2, 3.9, 1.7, 2.4		2.1
		Overall Mean	2.4
		Range	0.2 to 5.2
		Coefficient of Variation	50%

On the basis of these measurements, an indicator of fabric flex fatigue was chosen as the average number of cycles to the first appearance of a centrally located flex crack among four test specimens mounted at a single test station. Cycling was continued after the first instance of flex cracking until more extensive damage was sustained, generally at 10 or 20 million cycles. The appearance of the initial flex crack is illustrated in the photograph of Figure 13a; more extensive damage is shown in Figure 13b.

FLEX FATIGUE RESULTS

Measurements of the lifetime in flex of the experimental fabrics described in Table 5, which were tested on the flexing apparatus outlined in the previous section, are collected in Appendix C, Table C.1. Individual observations of the number of cycles to the first appearance of a centrally located flex crack are given for each specimen tested, and the extent of damage is summarized. The average lifetime of these fabrics ranged from a low of 140,000 cycles for 3 x 3 twill construction with high-twist filling yarns woven from Warp VII (10,080 denier yarn, 7 x 7 yarns/in., high-twist warp) to a high of 21.7 million cycles for a plain-weave construction with low-twist filling yarns from Warp I (5040 denier

INITIAL FAILURE
(1 MILLION CYCLES)

(a)

EXTENSIVE FAILURE
(10 MILLION CYCLES)

(b)

Figure 13 - Flex-Cracking in Rubber/Fabric Composites

yarn, 14 x 14 yarns/in., low twist warp). Initial cracking nearly always occurred on the outside, or tension side, of the bent specimen. The extent of damage ranged from "extensive" after 300,000 cycles to "not severe" after about 30 million cycles.

Several commercial fabrics designed for use in hovercraft skirt systems were also flexed under the same conditions; these included the Goodyear fabric (XA28A504-2A) used to first prove the tester (Tables 7 and 8), a similar fabric produced by Goodrich Tire and Rubber Co., and one from Avon Mfg. All were roughly the same strength and thickness as the experimental fabrics. Flex data for these fabrics are given in Appendix C, Table C.2. Lifetimes in flex were on average between 600,000 cycles (Avon) and 2.4 million cycles (Goodyear). (A Goodyear fabric with an additional thick layer of rubber added to one surface was also tested; it failed within 30,000 to 40,000 cycles, as also indicated in the table.)

The large effect of fabric construction on the flex-fatigue behavior of rubber/fabric composite materials is well illustrated by the test results for the experimental series of fabrics: flex lifetimes span over two orders of magnitude for materials differing only in fabric substrate construction. The task of sorting out those differences in fabric construction that result in significant differences in the ability of the composite to withstand high-curvature, high-frequency flexing has relied principally on the statistical technique of analysis of variance, or factorial analysis.[7,8,9] Limitations on the experimental design arising from the manner of varying fabric weave pattern and filling yarn twist level within a few specifically constructed warps, combined with budgetary restrictions limiting the number of constructions that could be tested, precluded attaining either a full or a balanced fractional design involving all five of the principal fabric construction variables: fiber denier, yarn denier, yarn twist, float length, and yarn crimp level. However, smaller, full-factorial blocks were analyzed. Average values of flex lifetime for all experimental fabrics of the twill weave pattern, which represent three levels of fiber denier and two levels of the remaining variables, are gathered in Table 9. (The 1 x 1 twill construction is, of course, the plain weave.)

Yarn crimp level in Table 9 is defined by the amount of twist in the yarns of the two fabric directions rather than by fabric direction itself, as originally intended, since the former method of distinction results in generally larger

comparative differences between crimp levels. For example, for both low or high twist yarns in the test direction that pass over low twist yarns in the opposite direction, the crimp level may be considered low, and when high twist yarns are crossed by either low or high twist yarns, the crimp level may be considered high. In those cases where the yarns in both the warp and filling directions have the same level of twist, the entry in Table 9 is the average of data obtained in the two directions. Those entry spaces in Table 9 marked by an "x" represent construction variable combinations that were unattainable: low twist/low crimp from high twist Warps IV and VII; and high twist/high crimp from low twist Warps I, III, V and VI. Empty entry spaces represent constructions woven but not tested because of budgetary restrictions.

TABLE 9 - AVERAGE FLEX LIFETIMES OF RUBBER-COATED EXPERIMENTAL FABRICS: TWILL WEAVES ONLY

FLEX LIFETIME (million cycles)

			FIBER DENIER							
			2 dpf		6 dpf		12 dpf			
			YARN DENIER		YARN DENIER		YARN DENIER			
YARN TWIST IN TEST DIRECTION			5040 (WARP VI)	10,080 (WARP VII)	5040 (WARP I)	10,080 (WARP III)	5040 (WARP IV)	10,080 (WARP V)	ROW AVERAGES	
LOW TWIST	1x1	LOW CRIMP	8.9	X	13.6	1.8	X	5.5	7.5	5.3
		HIGH CRIMP	6.3	0.6	8.8	1.1	3.6	2.6	3.8	
	3x3	LOW CRIMP	1.5	X	6.8	1.4	X	1.6	2.8	1.9
		HIGH CRIMP		0.5		1.6	0.8	1.1	1.0	
HIGH TWIST	1x1	LOW CRIMP	4.4	1.0	5.8	0.9	18.8	2.3	5.5	4.5
		HIGH CRIMP	X	0.6	X	X	2.4	X	1.5	
	3x3	LOW CRIMP	2.1		3.4	0.4		1.1	1.8	1.3
		HIGH CRIMP	X	0.14	X	X	0.8	X	0.5	
		COLUMN AVERAGES	4.6	0.6	7.7	1.2	5.3	2.4		
			2.6		4.1		3.7			

X — CONSTRUCTION NOT ATTAINABLE WITHIN PARTICULAR WARP

(empty) — CONSTRUCTION WOVEN BUT NOT TESTED

Although the significance of the five principal construction variables and their interactions cannot be examined directly by an analysis of variance of the entire data block of Table 9, smaller full-factorial blocks involving three or four of the variables in various combinations were split off and looked at separately. In addition, the effects of fiber type, fiber denier for the same fiber type, and weave pattern (twill or basket) were examined by direct comparison of the flex lifetimes of structures between which only these variables changed level.

EFFECT OF FIBER TYPE AND DENIER

The experimental fabrics represented by the data in Table 9 were constructed of nylon fibers of various types from two manufacturers. Sections of the low-twist Warp I were plain-woven with low-twist filling yarns of each of the principal fiber types in the deniers available in the range of interest (see Table 5). The effect of fiber type on flex lifetime for plain-weave constructions from Warp I consisting of 6 dpf, 5040 denier, low-twist yarns is shown in Table 10. The differences in flex lifetimes among 6 dpf DuPont Types 728 and 704 and Monsanto Type C02 fibers are not significant (at the 90% confidence level for a Student's t-test).

TABLE 10. EFFECT OF FIBER TYPE

	Flex Lifetime (million cycles)		
	Type 728	Type 704	Type C02
Warp I, 6 dpf, 5040 denier, low twist, plain weave, low crimp (filling direction only)	6.8	22.6	20.0
	6.8	22.6	19.6
	8.0	19.6	22.6
	>30.0	22.1	15.4
Mean	>12.9	21.7	19.4
CV (%)	88	7	15
Differences not significant (90%).			

The effects of fiber denier on the flex lifetime of similar constructions of the same fiber type but different deniers may be seen by comparison of the data in Table 11. Differences resulting from a change in fiber denier from 2 to 6 dpf for Monsanto Type C02 and from 6 to 12 dpf for DuPont Type 704 were found not to be significant (at both the 90% confidence level and at the 80% level).

TABLE 11 - EFFECT OF FIBER DENIER FOR FIBERS OF SAME TYPE

		Flex Lifetime (million cycles)			
		Type CO2 (Monsanto)		Type 704 (DuPont)	
		2 dpf	6 dpf	6 dpf	12 dpf
Warp I, 5040 denier, low twist,		1.4	15.4	19.6	--
plain weave, low crimp (fill-		9.1	19.6	22.1	18.3
ing direction only		26.4	20.0	22.6	26.0
		>31.6	22.6	22.6	19.6
	Mean	>17.1	19.4	21.7	21.3
	CV (%)	83	15	7	26
	Differences not significant (90%).				

Some additional estimates of the effect of fiber denier and information regarding interactions of this factor with the other fabric construction variables were obtained from the analyses of variance, and are described below. However, no information is available regarding possible interactive effects of fiber type, and, for purposes of this discussion, these effects have been assumed to be insignificant.

EFFECT OF WEAVE PATTERN

Since only a few basket-weave constructions were produced among the experimental fabrics, the effect of weave pattern (twill or basket) had to be assessed on the basis of a few direct comparisons between similar constructions. Flex lifetimes are compared in Table 12 for three distinct fabric categories woven in both the 3 x 3 twill and the 3 x 3 basket weave patterns. None of the differences between the three pairs of data were judged significant at the 90% confidence level, again on the basis of the Student's t-test. The twills are preferred, however, for their greater stability and ease of handling before adhesive and rubber coating.

TABLE 12 - EFFECT OF WEAVE PATTERN

Fabric Construction		Flex Lifetime (million cycles) 3 x 3 Twill	3 x 3 Basket
Warp I, 6 dpf, 5040 denier, high twist yarn, low crimp		1.9	2.4
		2.8	2.4
		3.9	2.8
		5.2	3.6
	Mean	3.4	2.8
	CV (%)	41	20
	Differences not significant (90%).		
Warp V, 12 dpf, 10,080 denier, low twist yarn, low crimp		0.6 1.9	0.9
		1.0 2.3	1.1
		1.0 2.3	1.5
		1.4 2.3	1.7
	Mean	1.6	1.3
	CV (%)	43	28
	Differences not significant (90%).		
Warp III, 6 dpf, 10,080 denier, high twist yarn, low crimp		0.3	0.3
		0.3	0.3
		0.6	0.3
		0.6	0.3
	Mean	0.4	0.3
	CV (%)	38	---
	Differences not significant (90%).		

ANALYSIS OF VARIANCE

Three full-factorial subsets of the body of flex data summarized in Table 9 and given individually in Appendix C were analyzed statistically for the significance of main and interactive effects of the fabric construction variables as follows:

Block A (Table 13) - fiber denier, yarn denier, yarn twist, and float length for filling direction tests only.

Block B (Table 14) - fiber denier, yarn denier, yarn twist, and fabric direction, as an indicator of yarn crimp, for plain-woven constructions only.

Block C (Table 15) - yarn denier, yarn twist and yarn crimp irrespective of fiber denier for plain-woven constructions only.

TABLE 13 - ANALYSIS OF VARIANCE OF FLEX-FATIGUE DATA: TWILL WEAVES, FILLING DIRECTION ONLY

BLOCK A

FLEX LIFETIME (million cycles)

TWIST IN TEST DIRECTION YARNS		FIBER DENIER: 2 dpf, YARN DENIER 5040 (WARP VI)	2 dpf, 10,080 (WARP VII)	6 dpf, 5040 (WARP I)	6 dpf, 10,080 (WARP III)	12 dpf, 5040 (WARP IV)	12 dpf, 10,080 (WARP V)	
LOW TWIST YARN	1 X 1	5.2 2.7 25.2 10.4 10.9	0.30 0.25 0.46 1.41 0.60	8.0 6.8 6.8 30.0 12.9	2.2 2.2 2.2 2.4 2.2	1.3 1.6 5.1 6.2 3.6	4.8 4 8 6.2 7.5 5.8	6.0
LOW TWIST YARN	3X3	0.15 0.41 1.9 3.4 1.5	0.14 0.14 0.8 1.1 0.5	2.8 9.7 9.7 5.2 6.8	0.5 0.8 0.9 1.0 0.8	0.15 0.15 1.3 1.6 0.8	0.6 1.0 1.0 1.4 1.0	1.9
HIGH TWIST YARN	1 X 1	1.6 7.0 2.4 6.6 4.4	0.30 0.36 0.25 1.41 0.58	8.0 9.3 2.8 3.0 5.8	0.5 1.0 1.0 1.1 0.9	0.8 0.8 1.0 1.2 1.0	0.8 1.1 2.6 4.8 2.3	2.5
HIGH TWIST YARN	3X3	0.4 0.7 1.6 5.7 2.1	0.02 0.03 0.22 0.30 0.14	2.8 3.9 5.2 1.9 3.4	0.3 0.3 0.6 0.6 0.4	0.15 0.15 1.3 1.6 0.8	1.0 1.0 1.0 1.4 1.1	1.3
		4.8	0.5	7.2	1.1	1.6	2.6	
		2.6		4.2		2.1		

	SIGNIFICANCE LEVEL (%)
MAIN EFFECTS:	
FIBER DENIER	95
YARN DENIER	99
YARN TWIST	99
FLOAT LENGTH	99
FIRST-ORDER INTERACTIONS:	
FIBER DENIER/YARN DENIER	99
FIBER DENIER/YARN TWIST	40
FIBER DENIER/FLOAT LENGTH	10
YARN DENIER/YARN TWIST	88
YARN DENIER/FLOAT LENGTH	91
YARN TWIST/FLOAT LENGTH	96

(None of the higher-order interactions were significant above the 90% level.)

TABLE 14 - ANALYSIS OF VARIANCE OF FLEX-FATIGUE DATA: PLAIN-WOVEN CONSTRUCTIONS ONLY

BLOCK B

FLEX LIFETIME (million cycles)

		FIBER DENIER						
		2 dpf		6 dpf		12 dpf		
		YARN DENIER		YARN DENIER		YARN DENIER		
		5040 (WARP VI)	10,080 (WARP VII)	5040 (WARP I)	10,080 (WARP III)	5040 (WARP IV)	10,080 (WARP V)	
LOW TWIST FILLING YARN	WARP	1.1	0.25	-	1.1	5.5	2.3	
		6.9	0.25	19.8	1.2	9.5	4.0	
		10.0	1.8	8.3	1.3	30.0	7.1	8.0
		10.0	1.8	15.6	1.6	30.0	7.1	
		7.0	1.0	14.6	1.3	18.8	5.1	
	FILL	5.2	0.30	8.0	2.2	1.3	4.8	
		2.7	0.25	6.8	2.2	1.6	4.8	
		25.2	0.46	6.8	2.2	5.1	6.2	6.0
		10.4	1.41	30.0	2.4	6.2	7.5	
		10.9	0.60	12.9	2.2	3.6	5.8	
HIGH TWIST FILLING YARN	WARP	118	0.24	4.1	0.8	0.9	1.8	
		3.4	0.24	6.7	1.2	1.3	2.7	
		10.0	1.8	10.7	1.2	4.4	2.7	3.9
		10.0	1.2	13.6	1.3	8.5	3.0	
		6.3	0.6	8.8	1.1	3.8	2.6	
	FILL	1.6	0.30	8.0	0.5	0.8	0.8	
		7.0	0.36	9.3	1.0	0.8	1.1	
		2.4	0.25	2.8	1.0	1.0	2.6	2.5
		6.6	1.41	3.0	1.1	1.2	4.8	
		4.4	0.58	5.8	0.9	1.0	2.3	
		7.1	0.7	10.5	1.4	6.8	4.0	
		3.9		6.0		5.4		

	SIGNIFICANCE LEVEL (%)
MAIN EFFECTS:	
FIBER DENIER	78
YARN DENIER	99
YARN TWIST	99
FABRIC DIRECTION	91
FIRST-ORDER INTERACTIONS:	
FIBER DENIER/YARN DENIER	97
FIBER DENIER/YARN TWIST	76
FIBER DENIER/FABRIC DIRECTION	88
YARN DENIER/YARN TWIST	98
YARN DENIER/FABRIC DIRECTION	93
YARN TWIST/FABRIC DIRECTION	24
HIGH-ORDER INTERACTIONS:	
FIBER DENIER/YARN DENIER/ FABRIC DIRECTION	91

(No other high-order interactions were significant above the 90% level.)

TABLE 15 - EFFECT OF YARN CRIMP IRRESPECTIVE OF FIBER DENIER: PLAIN WEAVES ONLY

BLOCK C

FLEX LIFETIME (million cycles)

	YARN DENIER 5040, YARN TWIST LOW	YARN DENIER 5040, YARN TWIST HIGH	YARN DENIER 10,080, YARN TWIST LOW	YARN DENIER 10,080, YARN TWIST HIGH	
LOW CRIMP	1.1 6.9 15.6 19.8 10.9*	5.5 9.5 30.0 30.0 18.8	1.2 1.2 7.1 7.1 4.2*	0.25 0.25 1.8 1.8 1.0	8.7
HIGH CRIMP	1.3 1.6 5.1 6.2 3.6	0.8 0.8 1.0 1.2 1.0	0.30 0.25 0.46 1.41 0.60	0.30 0.36 0.25 1.41 0.58	1.5
	7.2	9.8	2.3	0.8	
	8.6		1.6		

LOW CRIMP	WARP I, WARP VI low-twist filling, warp dir.	WARP IV low-twist filling, warp dir.	WARP III, WARP V low-twist filling, warp dir.	WARP VII low-twist filling, warp dir.
HIGH CRIMP	WARP IV low-twist filling, filling dir.	WARP IV high-twist filling, filling dir.	WARP VII low-twist filling, filling dir.	WARP VII high-twist filling, filling dir.

	SIGNIFICANCE LEVEL (%)
MAIN EFFECTS:	
YARN DENIER	99
YARN TWIST	20
YARN CRIMP	99
FIRST-ORDER INTERACTIONS:	
YARN DENIER/YARN TWIST	69
YARN DENIER/YARN CRIMP	98
YARN TWIST/YARN CRIMP	63

(HIGH-ORDER INTERACTION NOT SIGNIFICANT)

*Two high and two low entries from combined data for the two warps given.

Although all of the entries on Block A (Table 13) are for filling direction tests, the crimp level was not held truly constant since all filling yarns in fabrics woven from Warps I, III, V and VI crossed low-twist warp yarns and, hence, were at a lower level of crimp, in general, than filling yarns of the same twist level in fabrics woven from high-twist Warps IV and VII. If results were to show either a strong effect of crimp on flex lifetime or a strong interaction between yarn crimp and the other fabric construction variables, this "impurity" in the design of Block A would have to be taken into account in interpretations of the results.

In Block B for plain-weaves, data obtained in both the warp and filling directions of each fabric are used to get some indication of the effect of yarn crimp. Crimp in the filling direction was always greater than the crimp in the warp direction, although the difference was not always large.

The effect of yarn crimp can be better assessed from Block C, where the entries were chosen to represent the two extremes of yarn crimp for each yarn denier/yarn twist combination, regardless of the fiber denier used in the construction. The lowest crimp level for low-twist 5040 denier yarn constructions occurred in the warp direction of fabrics from low-twist Warps I and VI. The highest crimp for these low-twist yarns was found in the filling direction of high-twist Warp IV, as indicated below the data block in Table 15. Similarly, the lowest and highest crimp condition for high-twist 5040 denier yarns occurred in the warp and filling directions, respectively, of high-twist Warp IV. Where sets of data for two fabrics fulfilling the yarn denier/twist/crimp condition were available, the two high and two low values from the combined set of eight individual test results were used in the analysis, as indicated in Block C (Table 15) by an asterisk. The penalty paid for inclusion of crimp level with greater precision in the analysis in this way is, of course, that yarn crimp/fiber denier interactions confounded the results.

The results of the analysis of variance of each of the three Blocks are given, along with the respective data, in Tables 13, 14, and 15, and summarized in Table 16. Interpretation of the sometimes conflicting estimates of significance for the various main and interactive effects in the three separate blocks is not entirely straightforward and must rely on what is known about the confounding of factors within each block. There was an unequivocally significant (99%) main

TABLE 16 - SUMMARY OF MAIN AND INTERACTIVE EFFECTS OF FABRIC CONSTRUCTION VARIABLES FROM ANALYSIS OF VARIANCE

	Significance Level (%)		
	Block A*	Block B**	Block C***
MAIN EFFECTS:			
Fiber Denier	95	78	--
Yarn Denier	99	99	99
Yarn Twist	99	99	20
Float Length	99	--	--
Yarn Crimp	--	91	99
FIRST-ORDER INTERACTIVE EFFECTS:			
Fiber Denier/Yarn Denier	99	97	--
Fiber Denier/Yarn Twist	40	76	--
Fiber Denier/Float Length	10	--	--
Fiber Denier/Yarn Crimp	--	88	--
Yarn Denier/Yarn Twist	88	98	69
Yarn Denier/Float Length	91	--	--
Yarn Denier/Yarn Crimp	--	93	98
Yarn Twist/Float Length	96	--	--
Yarn Twist/Yarn Crimp	--	24	63
Float Length/Yarn Crimp	--	--	--
SIGNIFICANT HIGHER-ORDER INTERACTIONS:			
Fiber Denier/Yarn Denier/Yarn Crimp	--	91	--

*Block A - $3^1 2^3$: Fiber Denier, Yarn Denier, Yarn Twist, Float Length (filling direction only)

**Block B - $3^1 2^3$: Fiber Denier, Yarn Denier, Yarn Twist, Fabric Direction (plain weave only)

***Block C - 2^3: Yarn Denier, Yarn Twist, Yarn Crimp; independent of Fiber Denier (plain weave only)

effect of yarn denier, with lower denier favored, in each of the three blocks. The main effect of yarn crimp was also highly significant (99%) in Block C, where it was represented at its extremes and also significant (91%), although less forcefully so, in Block B where it was represented by the smaller crimp differences between warp and filling fabric direction; a lower crimp level resulted, in general, in a longer flex lifetime. A 1 x 1 float length (plain-weave) was also significantly (99%) favored over a float-length of 3 x 3 in Block A, the only block in which its effects were measured. There seems no reason to doubt this conclusion since all but one of the fourteen comparisons of the lifetimes of similar fabrics at the two levels of float length (which may be made from the data in Table 9) showed a longer lifetime for the plain-woven version.

The real significance of the main effects of fiber denier and yarn twist is more difficult to determine from the results of the factorial analyses. The effect of fiber denier was not found to be significant (<90%) in Block B where the effect of fabric direction was substituted for yarn crimp; neither was it found significant in the comparisons in Table 11. However, in Block A, fiber denier was significant at the 95% level. Probably this latter estimate reflects the confounding effect of differing yarn crimp levels in Block A and that fiber denier is, in reality, not significant as a main effect. If this is so, we may have greater confidence in the results of the analysis of Block C in which it was assumed that fiber denier plays an insignificant role.

In Block C the effect of yarn twist was found to be insignificant as a main effect, while in both Blocks A and B yarn twist was estimated as significant at the 99% confidence level. In Block C the effect of yarn twist is straightforwardly estimated, unencumbered by the effects of other variables except fiber denier. However, the fiber denier/yarn twist interaction is insignificant in both Blocks A and B and the effect of fiber denier can, therefore, probably be discounted. Thus, it would seem that the estimate of the effect of yarn twist in Block C is the "true" result, while those from Blocks A and B actually reflect the confounding effect of a relatively uncontrolled yarn crimp in these blocks.

It is not clear whether the strong interaction indicated between fiber denier and yarn denier in Blocks A and B is real or the result of the undefined effects of yarn crimp. However, the fairly strong three-way interaction between fiber denier, yarn denier and yarn crimp (fabric direction) in that Block B would seem

to suggest the latter. In addition, if we assume that fiber denier was insignificant as a main effect, as discussed earlier, its interactive effects are less likely to have been significant. No other interactions involving fiber denier were significant.

The yarn denier/float length and yarn denier/yarn crimp interactions were both significant, whereas the yarn denier/yarn twist interaction probably was not. Since the absolute level of both yarn crimp and float length depends on the denier of the yarns (and yarn count of the structure), it is not surprising that these factors should exhibit significant interactions with yarn denier.

In summary, the fabric construction variables that most influenced flex-life of rubber-coated fabrics were yarn denier, yarn crimp level, and fabric float length. The preferred levels or directions of each of the five variables studied, determined from the analysis of variance and by direct comparison of the data for similar fabrics given in Tables 9, 13, 14 and 15, are listed in Table 17. The fabrics among those studied with the longest average lifetime in flex--21 million cycles (see Appendix C)--were plain-woven from low-twist, 5040 denier yarns that contained 6 or 12 denier filaments.

TABLE 17 - PREFERRED DIRECTION OF FABRIC CONSTRUCTION VARIABLES

Factor	Significance Level (%)	Preferred Level or Direction
Fiber Denier	--*	6 or 12 dpf
Yarn Denier	99	5040
Yarn Twist	--*	low
Float Length	99	1 x 1
Yarn Crimp	99	low
Weave Pattern	<90	twill or basket

*Conflicting estimates because of confounding of results with crimp level. See text.

EFFECT OF FABRIC SUBSTRATE THICKNESS

Fabric substrates constructed from low denier, low-twist yarns naturally have lower yarn crimp levels and, as a consequence, are thinner than fabrics of the same weight woven from higher-denier, high-twist yarns. The relationship between fabric substrate thickness and flex lifetime was significantly higher for the

experimental fabrics (measured in the filling direction) is graphed in Figure 14 (and tabulated in Appendix A, Table A.4). Flex lifetime was significantly higher among those fabrics represented in the region of lowest substrate thickness.

Since all of the fabric substrates tested were about the same weight, and the same weight of coating material was applied to each, the total thickness after coating of each fabric in the series was about the same. Therefore, the rubber layer covering the fabric knuckles in the composite structure was thicker when the fabric substrate was thinner. Thickness of the rubber layer also varied more in those composites containing the thicker, more open weaves. The contours of the rubber layers in the filling direction of several fabric constructions representing a wide range of flex lifetimes are presented in Figure 15; these profiles were taken from photographs of fabric cross sections such as those of Figures 5 through 8. In general, fabrics with a more uniformly thick rubber covering layer were most resistant to flex-cracking.

Examination of failed specimens that were flexed until extensive damage had been done showed that the rubber tends to crack in the thin regions covering the knuckles, or floats, or the yarns running in the opposite direction to those being flexed. As a result, the pattern of flex cracks takes on the image of the underlying fabric weave pattern in the damaged specimens, as illustrated in Figure 16. The thin regions of rubber at the composite surface on the outside of the bend are subject to the greatest tensile strains imposed by the bent configuration and are additionally vulnerable because of stress concentrations in these areas.

Lower yarn denier, lower yarn twist, and lower yarn crimp all result in lower fabric knuckle height, as shown in the fabric cross sections of Figures 5 through 8. Lower knuckle height results in a more uniformly thick rubber layer, as shown in Figure 15. However, it is difficult to see from either Figures 5 through 8 or from Figure 15 any advantage in the rubber-layer thickness or contour of the plain weaves as compared to the 3 x 3 twills. Perhaps the performance of the longer float twills (or basket-weaves) was significantly poorer than that of the plain weaves because the longer thin rubber regions running in the direction perpendicular to the flexed direction in the twills had an increased probability of failure during any cycle of flex.

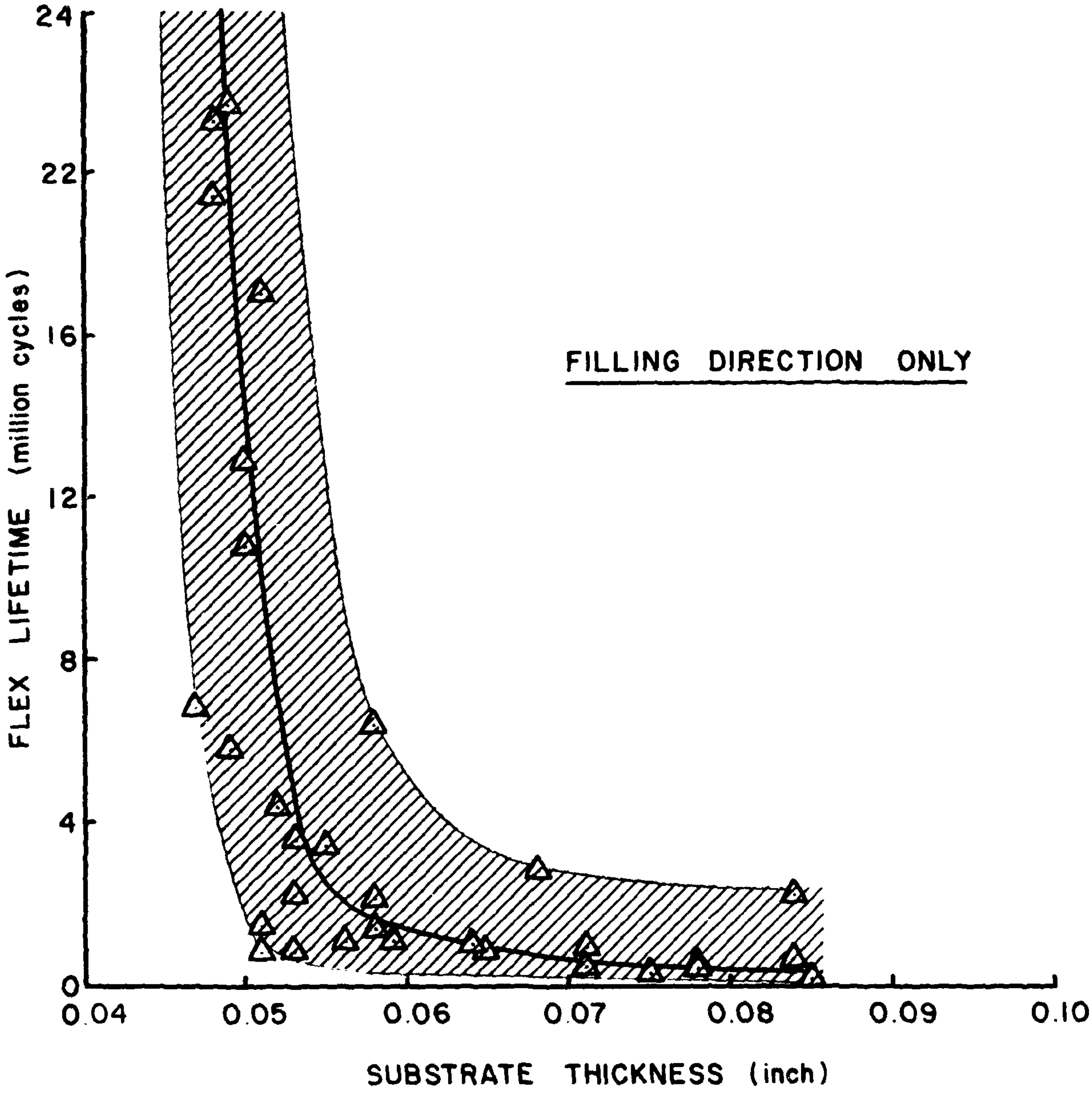


Figure 14 - Variation of Flex Lifetime of Rubber/Fabric Composites with Fabric Substrate Thickness

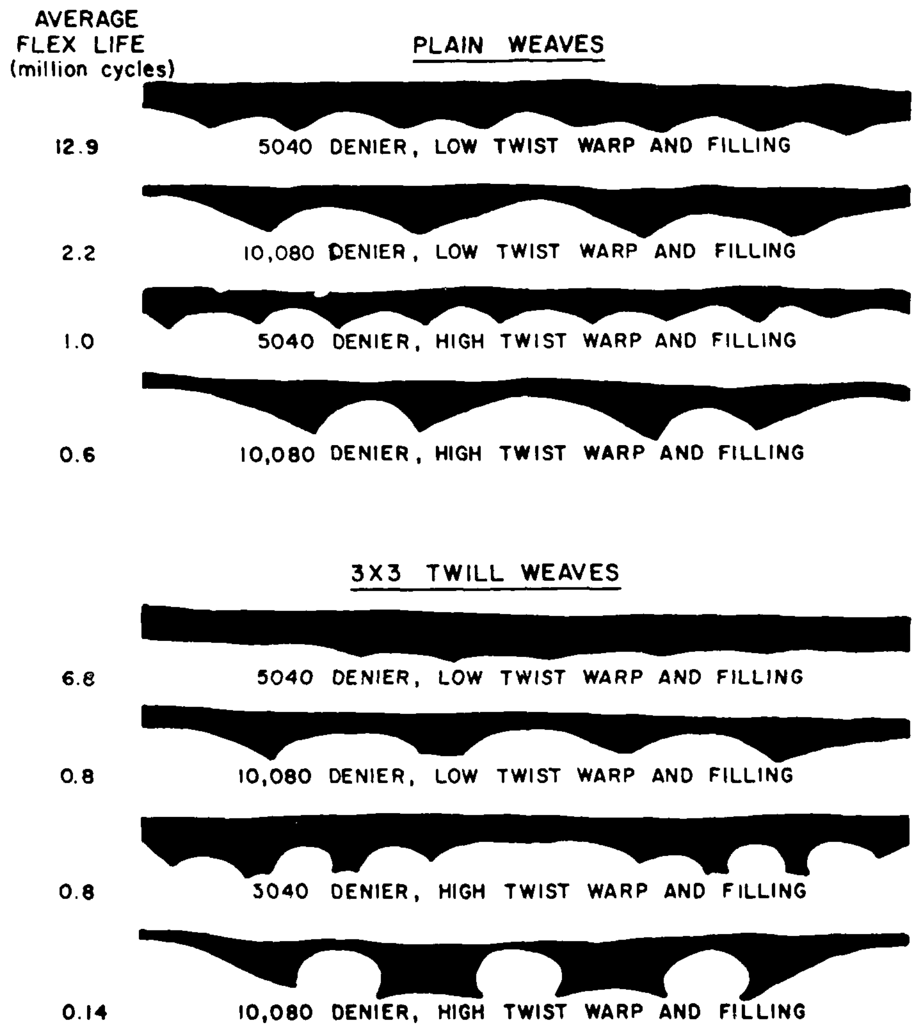


Figure 15 - Profiles of Rubber-Layer in Several Rubber/Fabric Composites (Filling Direction)

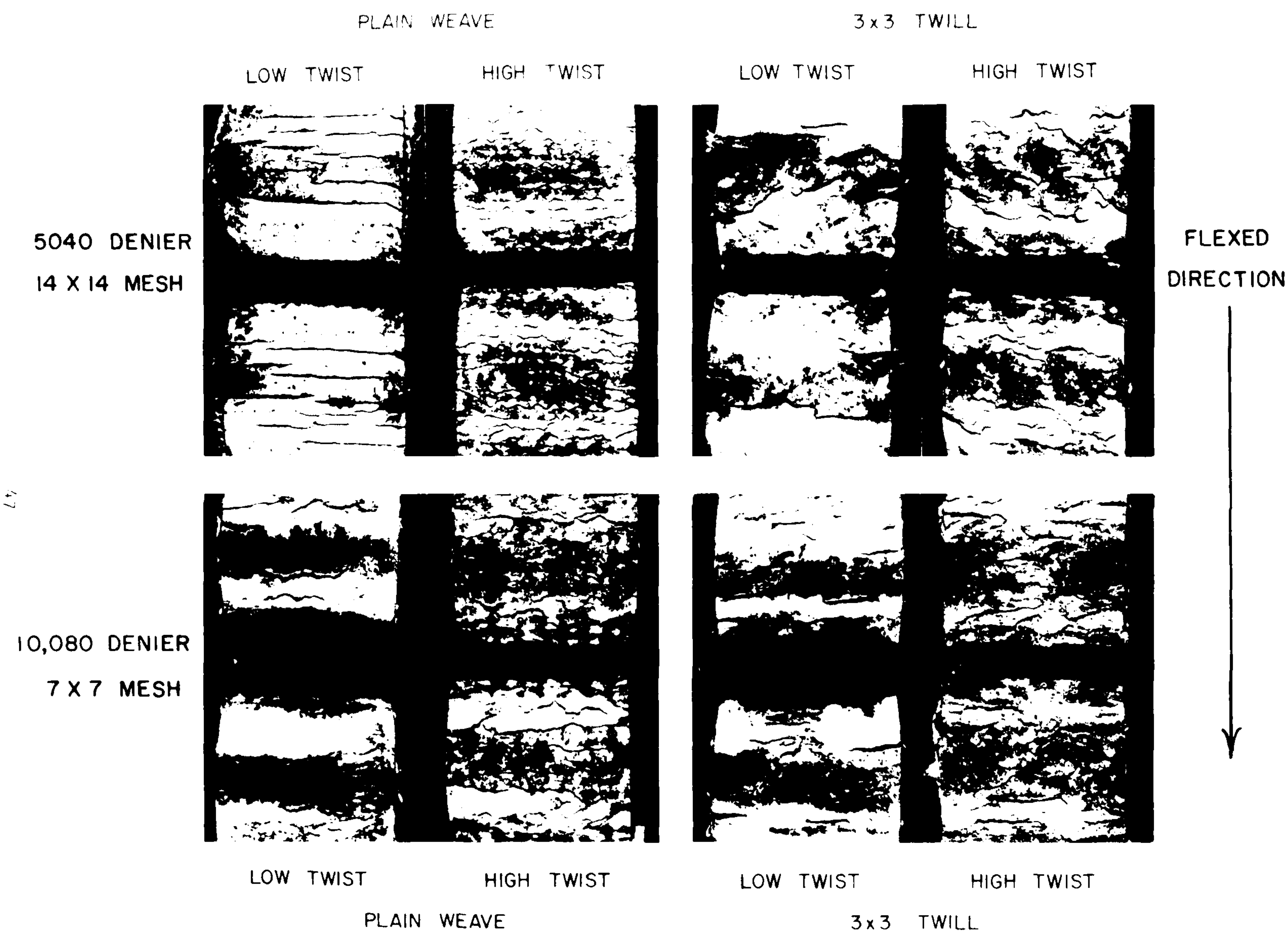


Figure 16 – Flex-Crack Patterns in Rubber/Fabric Composites with Different Substrate Constructions (Tension Side of Bend)

It was impossible, however, within the bounds of the experimental design, to separate the effects of the fabric construction variables as they influence fabric and rubber-layer thickness from other effects that fabric construction may exert directly on fabric performance. Fiber strains, the number and nature of inter-fiber contact forces, and ultimately the level of frictional losses within the composite material as it is bent through multiple cycles of curvature depend in complicated ways on the yarn and fabric structure and on the level of bonding.

EFFECT OF ADHESIVE BONDING AND FLEXURAL RIGIDITY

High-frequency drum impact tests on skirt fabrics from several sources which are being conducted separately at DTNSRDC, have shown the AI series of experimental fabrics to perform poorly relative to some commercial fabrics produced by the Goodyear and Goodrich rubber companies. In fact, the level of adhesive bonding between the rubber layers and the fabric substrate, as measured by the strip peel test (see Appendix B), was quite low (20 to 25 lb/in., Appendix A), in those of the experimental fabrics with little or no open area to permit bridging of the rubber through the substrate structure; however, more open fabrics, in which bridging occurred, reached acceptable levels of peel strength (48 lb/in., Appendix A). We decided that some of the experimental fabrics should be rubber-coated by one of the commercial skirt material manufacturers so we could compare performance, particularly in drum impact but also in flex-cycling. Goodyear Aerospace subsequently rubber-coated approximately one square-yard pieces of several of the experimental fabrics; their proprietary adhesive and natural rubber/polybutadiene rubber formulation NA555 were applied; final fabric thickness varied between 0.12 and 0.14 in.--thicker than the materials coated at AI, which averaged 0.10 in. in thickness.

Although some difficulty was encountered in determining the peel strength of the Goodyear-coated fabrics, such results as were achieved (Appendix A, Table A.4) indicate no consistent or dramatic increase in adhesive bond strength above the levels obtained in the fabrics coated at AI. Four of the Goodyear-coated materials were flex-tested under the same conditions as were their counterparts coated at AI; the AI-coated fabrics performed consistently better in flex as summarized in Table 18 (individual measurements are given in Appendix C, Table C.3). Some reverse correlation is indicated in Figure 17 between lifetime in flex and level

of adhesive bonding: structures that were more open and exhibited the greatest peel strengths generally performed more poorly in flex.

No correlation was found between flex lifetime and the flexural rigidity of the various rubber/fabric composite structures (Figure 18). (Values of flexural rigidity for each fabric construction are given in Appendix A and the method of determination described in Appendix B.)

TABLE 18 - COMPARISON OF AVERAGE FLEX LIFETIMES OF FABRICS COATED AT ALBANY INTERNATIONAL RESEARCH AND AT GOODYEAR

Fabric Construction	Flex Lifetime (million cycles)		Ratio
	Coated at AI	Coated at Goodyear	AI/Goodyear
Warp V, Type 704 nylon, 12 dpf, 10,080 denier yarn, 7 x 7, low twist warp:			
plain weave, low twist filling	5.8	2.6	2.2
3 x 3 twill weave, low twist filling	1.0	0.37	2.7
Warp VI, Type C02 nylon 2 dpf, 5040 denier yarn, 14 x 14, low twist warp:			
plain weave, low twist filling	>7.0	>6.3	~1
Warp VII, Type C02, 2 dpf, 10,080 denier yarn, 7 x 7, high twist warp:			
plain weave high twist filling	<0.58	0.35	1.6

DESIGN OF BROAD FABRICS FOR SKIRT TRIALS ON SRN4 CRAFT

Manufacture of three rubber-coated fabrics, in widths and lengths sufficient for full-scale skirt panel construction, was next required. Two of these broad fabrics were to be designed to duplicate closely the construction of the fabric substrate in Goodyear skirt fabric, GAC 591; the base fabric in this material is designated RF-477 and is a 10 x 10 count, plain-weave woven from 4/2/840/12S/7Z, 6 dpf nylon yarn. The choice of this fabric design was based on the superior performance of GAC 591 in the DTNSRDC drum impact test. This performance is, in large part, attributable to the high adhesive strength resulting from the large

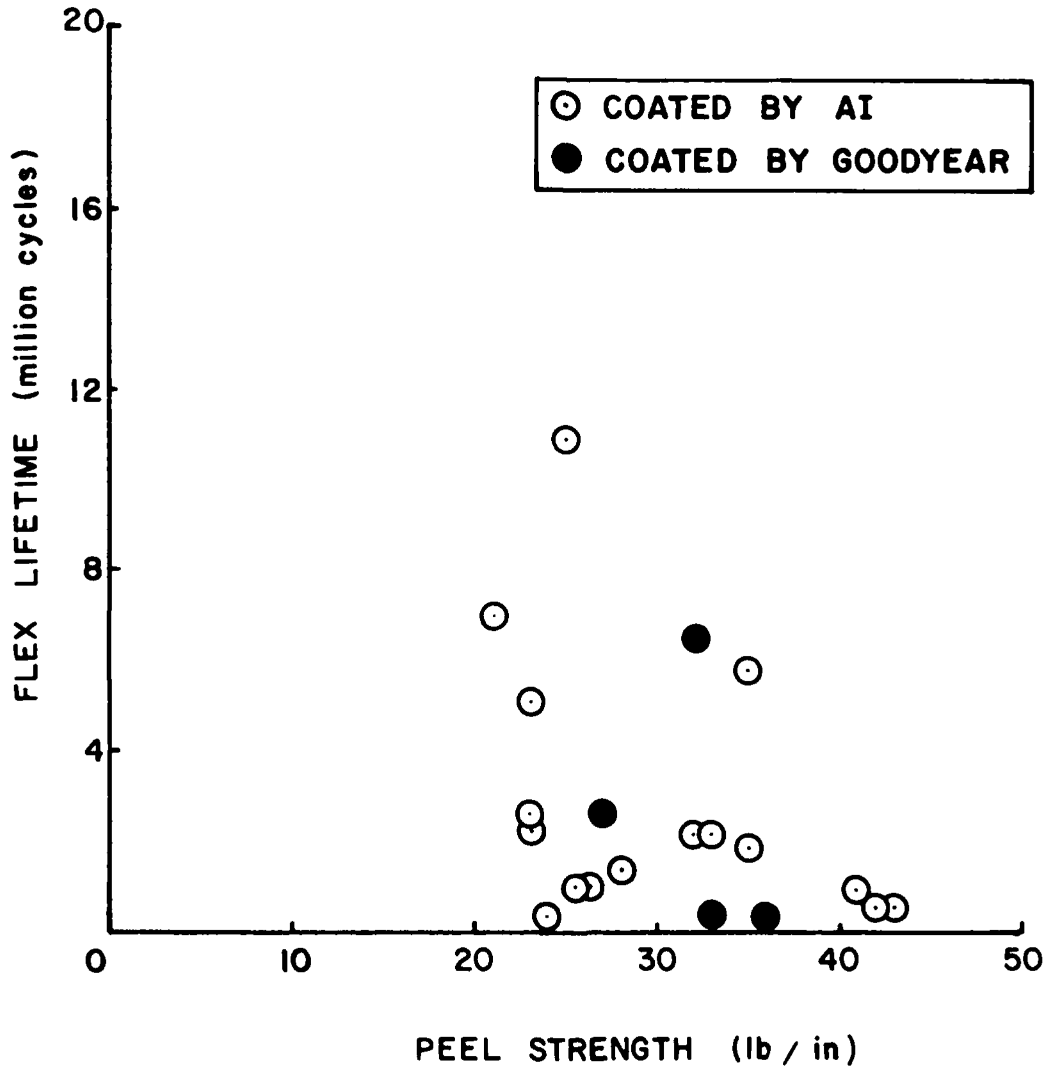


Figure 17 - Relationship Between Flex Lifetime and Peel Strength for Rubber/Fabric Composites

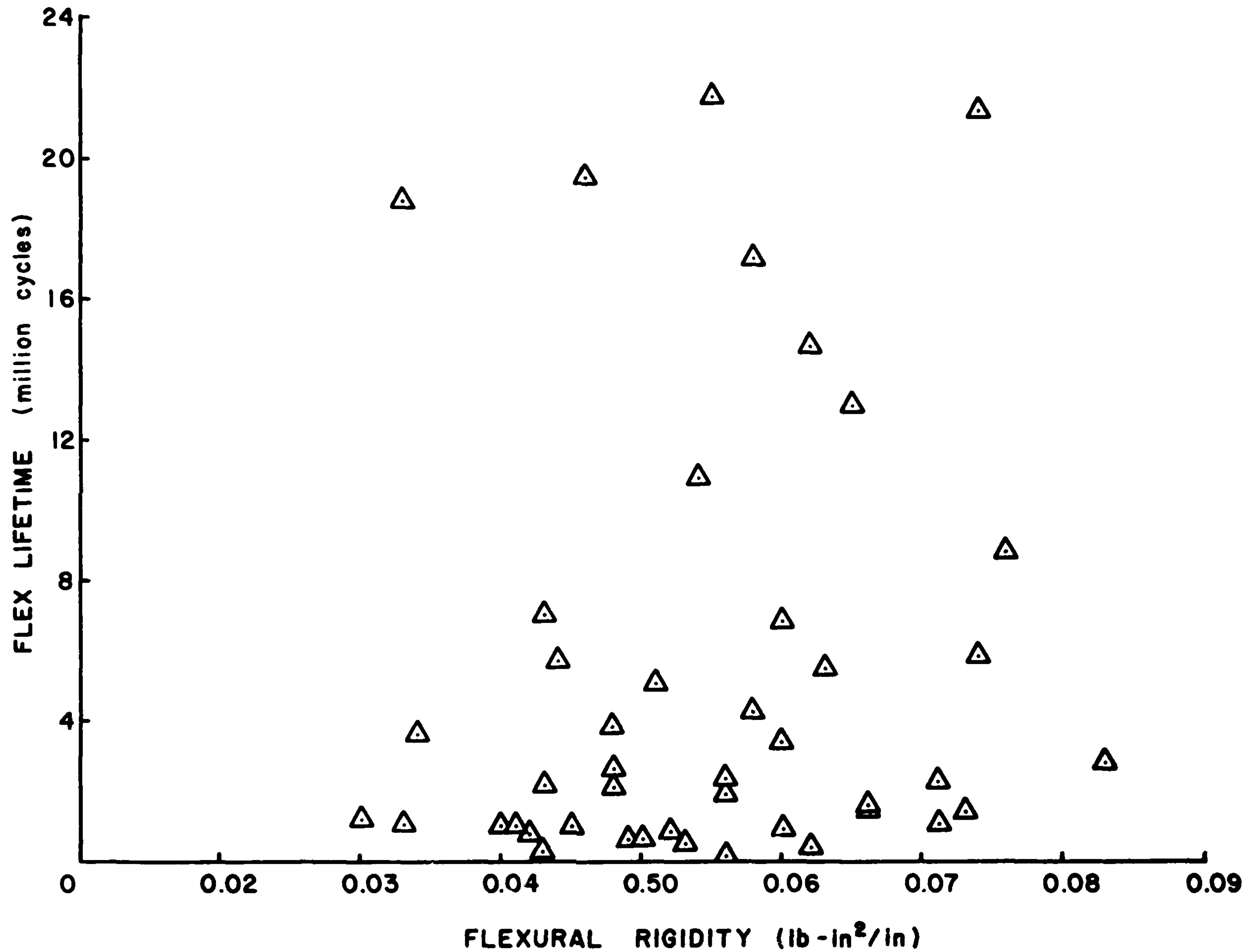


Figure 18 - Relationship Between Flex Lifetime and Flexural Rigidity of Rubber/Fabric Composites

fabric pores available for rubber penetration and bridging. One of these two broad fabrics modelled after the Goodyear design was to be rubber-coated by Goodyear Aerospace Corp. and the other, by the B. F. Goodrich Co., both of Akron, Ohio.

Design of a third trial fabric was based on the use of a novel yarn construction--a wrapped, or covered, yarn of slightly lower total denier (5880) than the 6720 denier plied yarns used in GAC 591. The purpose of this proposed construction was to maintain a round-yarn configuration and, therefore, significant free open area, but without using highly twisted yarns. Flex-testing of the experimental series of fabrics had not yet been completed when this design was proposed, but the many test results available at that time indicated a strong effect of yarn twist on flex lifetime as in Blocks A and B, Tables 13 and 14. It now appears from the complete analysis of variance that the perceived effect of yarn twist <u>per se</u> is not significant in relation to the experimental error, or variation, in test results. Nevertheless, the overall average flex lifetime for each "low-twist" row in Table 9 is greater than for the comparable "high-twist" row, and the design of the third broad fabric offers the potential of eliminating any deleterious effects of highly twisted yarns.

The wrapped yarns, whose structure is depicted schematically in Figure 19, were produced by Fabric Development, Inc. of Quakertown, PA, using a 70 denier, 34 filament Type 380 DuPont nylon covering yarn applied at 27 wraps per inch. The quality of the yarn produced was reasonably good and uniform. A 10 x 10 count, plain-weave fabric was subsequently produced from this yarn. Some difficulty was encountered during weaving, because the covering of the warp yarns stripped back as the yarns passed through the heddles. The quality of this fabric was uneven.

Details of the construction of each of the three broad fabrics are given in Table [illegible]. The ply twist of the plied-yarn fabrics was adjusted to give a balanced, or torque-free, structure. Each of the three broad fabrics was scoured and heat-set by the same methods employed in the finishing of the experimental fabrics and described in Appendix B. The finished fabrics before coating are illustrated in Figure 20. One of the plied yarn fabrics and the wrapped-yarn fabric were rubber-coated by Goodyear Aerospace Corp.; the second plied-yarn fabric was coated by B. F. Goodrich. Both companies used proprietary adhesives and natural rubber/polybutadiene formulations for the coating material, which was applied in

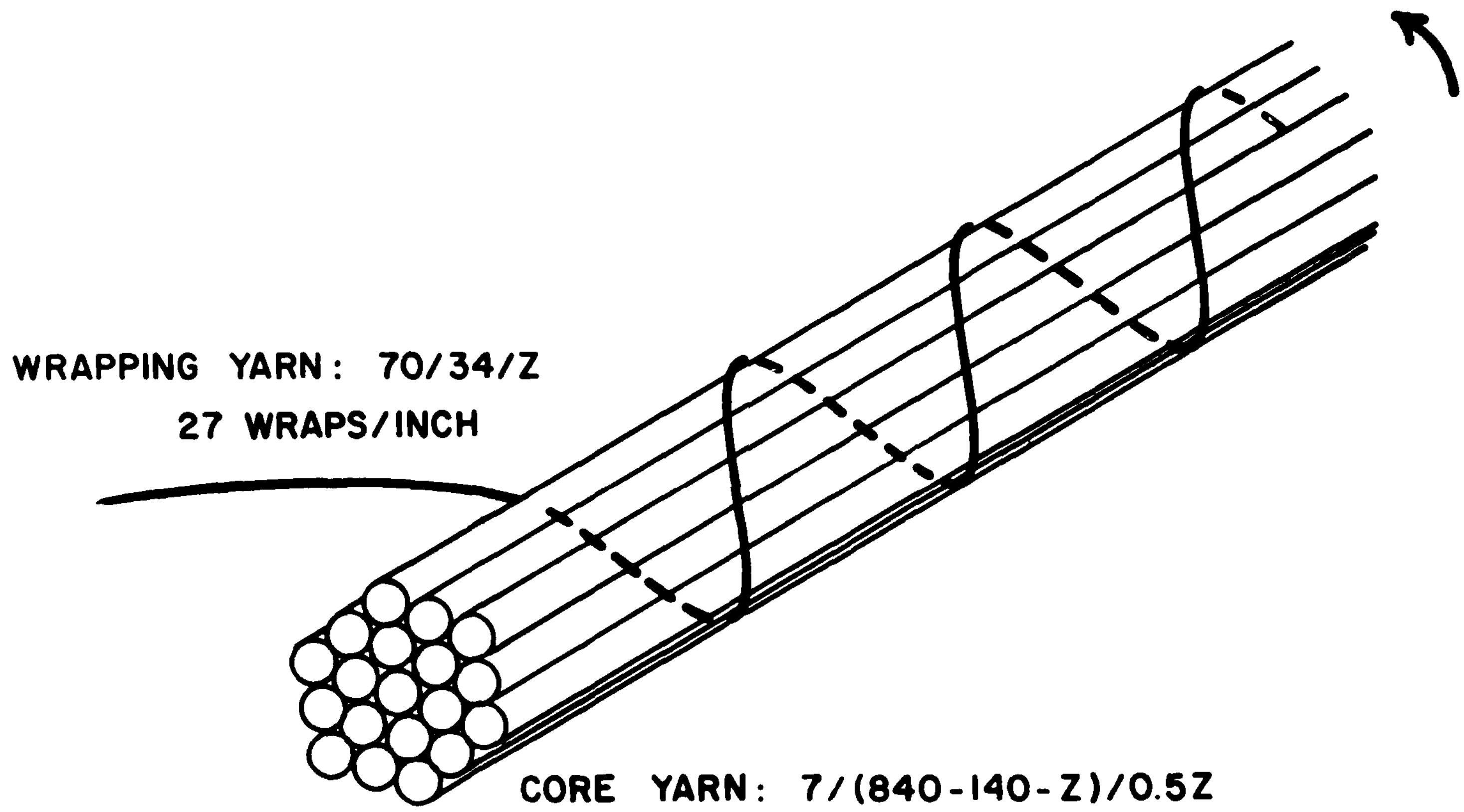
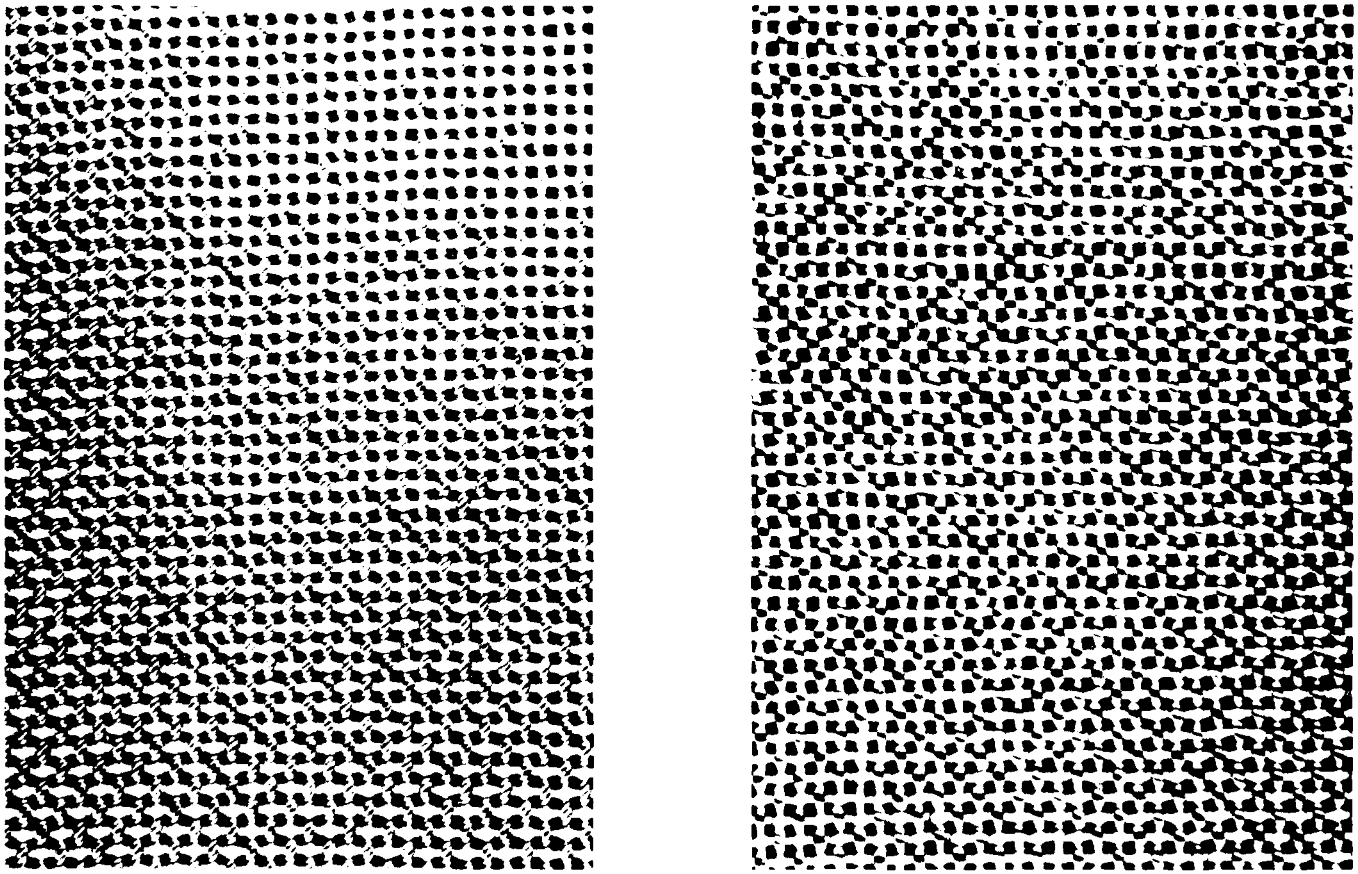


Figure 19 - Wrapped Yarn Construction



PLIED YARN CONSTRUCTION
4/(1680-280-TYPE 728)/12S/5Z

WRAPPED YARN CONSTRUCTION
7/(840-140-Z-TYPE 728)/0.5Z
70 DENIER WRAPPING YARN,
27 WRAPS/INCH

[illegible] for Skirt Trials on SRN4 Craft: Plain-[illegible], [illegible] x 10

sheet form by calender rolls. The coated fabrics were shipped directly to DTNSRDC and will be used to prepare skirt panels for trials on the English Channel-crossing hovercraft, the SRN4.

TABLE 19 - BROAD FABRICS FOR SKIRT TRIALS ON SRN4 CRAFT

Yarn Construction	Fabric Construction	Weight (oz/yd^2)		Thickness (in.)		Coating
		Uncoated	Coated	Uncoated	Coated	
1. 4/(1680-280-Type 728)/12S/5Z	plain weave 10 x 10	25	110	0.072	0.137	Goodyear - same adhesive and natural rubber/polybutadiene formulation used for GAC 591
2. 4/(1680-280-Type 728)/12S/5Z	plain weave 10 x 10	25	117	0.072	0.142	Goodrich - natural rubber/polybutadiene formulation 7815
3. 7/(840-140-Z-Type 728)/0.5Z Wrapped with 70 denier yarn at 27 wraps/inch (3-4% of total yarn weight)	plain weave 10 x 10	18	95	0.060	0.116	Goodyear - same adhesive and natural rubber/polybutadiene formulation used for GAC 591

Samples of these three trial fabrics were cycled on the flex tester under the same conditions used for flexing of the experimental fabrics. Individual test results are given in Appendix C, Table C.4. The plied-yarn fabric coated by Goodrich has an average flex lifetime of 4.4 million cycles in the warp direction and 3.4 million cycles in the filling direction; that coated by Goodyear had an average flex lifetime of only 1.2 million cycles in the warp direction and 1.3 million cycles in the filling direction. Both fabrics were 0.14 in. thick. The wrapped-yarn fabric, 0.12 in. thick, had a greater flex lifetime in the warp direction, 4.3 million cycles, and in the filling direction, 1.6 million cycles, than the plied-yarn fabric also coated by Goodyear. The much better performance of the wrapped-yarn fabric in the warp direction probably results from the considerably lower warp crimp in this fabric compared with the more balanced crimp in the plied-yarn fabrics, as illustrated in the fabric cross sections presented in Figure 21.

Although none of the three broad fabrics was distinctly superior to the other two in the laboratory flex-test, the sea trials, during which the fabrics will be subjected to high-speed impact in addition to the high-curvature flexing, may differentiate more fully among them.

WARP DIRECTION →

a PLIED-YARN FABRIC, RUBBER-COATED BY GOODYEAR

b PLIED-YARN FABRIC, RUBBER-COATED BY GOODRICH

c. WRAPPED-YARN FABRIC, RUBBER-COATED BY GOODYEAR

Figure 21 - Cross-Sections of Rubber-Coated Fabrics for Skirt Trials on SRN4 Craft: Plain-Weaves, 10 x 10

RECOMMENDATIONS FOR DESIGN OF SKIRT FABRICS

The flex-fatigue studies reported here and the work with the drum impact tester carried on independently at DTNSRDC (data not yet published) have identified some of the structural characteristics of the fabric substrate in rubber/fabric composites that lead to good performance as an SEV skirt material. To resist flex-cracking over many cycles of high-frequency, high-curvature bending, thinner fabric substrates composed of lower denier, lower crimp yarns are preferred. Resistance to delamination during high-energy impact, however, requires levels of rubber-to-fabric adhesion that, for the present at least, are best achieved when the structure is mechanically interlocked by "bridges" of rubber formed in the fabric pores. Unfortunately, the need for an appreciably open fabric structure with large pores for rubber strike-through is somewhat incompatible with fabric design features that promote long lifetimes in flex: thinner, lower crimp structures with sufficient yarn density to meet the tensile and tearing strength requirements generally have little or no free open area.

How can these opposing needs for flex and impact resistance both be satisfied in the design of a fabric substrate for SEV skirt materials? One solution is to use a fiber stronger than the nylon (or polyester) yarns currently in use. A stronger material would permit a lower yarn density in a thinner fabric having greater free open area.

DuPont's Kevlar 29 fiber achieves a tenacity of about 16 gpd in low-crimp woven structures, in contrast to a maximum of about 8 gpd for high-tenacity nylon or polyester. Perhaps the higher strength of this material can be exploited in the design of fabrics such as those outlined in Table 20. In this table the maximum number of ends of Kevlar 29 weavable in a square, plain-weave construction is compared with the number needed to meet the strength criterion at 1200 lb/in. With yarn deniers of 1000 and above sufficiently strong fabrics can be made without jamming. Round-yarn diameter, free fabric open area, and fabric thickness are also estimated for yarn deniers between 1000 and 6000 in the manner indicated in the table.

The entries in Table 20 reveal that a suitably strong, thin, and open plain-weave fabric substrate could be constructed from 1500 denier Kevlar 29 yarns woven 23 ends to the inch or from 2000 denier Kevlar 29 yarn woven 17 yarns to the inch. Such fabrics with some degree of crimp balance should be between 0.04 to 0.05 in.

TABLE 20 - SUITABLE YARN DENIERS AND FABRIC COUNTS FOR KEVLAR 29 FABRICS DESIGNED FOR USE IN SURFACE EFFECT VEHICLE SKIRT PANELS

Yarn Denier	Fabric Ends per Inch: Maximum Weavable in Square Plain Weave[4]	Fabric Ends per Inch: Number Required to Achieve [illegible] lb/in. Tensile Strength (at [illegible] gpd)	Calculated Yarn Diameter* (in.)	Maximum Free Open Area** (%)	Calculated Fabric Thickness: For Balanced Crimp***	Calculated Fabric Thickness: For Maximum Crimp†
1000	36-41	[illegible]	[illegible]	27	[illegible]	0.042
1500	29-34	[illegible]	0.017	37	[illegible]	0.051
2000	25-29	[illegible]	[illegible]	43	[illegible]	0.060
3000	21-24	[illegible]	[illegible]	50	[illegible]	0.072
4000	18-20	[illegible]	0.028	58	[illegible]	0.084
4500	17-19	[illegible]	0.030	58	0.060	0.090
5000	16-18	[illegible]	[illegible]	60	[illegible]	0.096
6000	15-17	[illegible]	0.036	61	[illegible]	0.108

*Yarn diameter (in.) = $\left[\dfrac{4 \times \text{denier}}{\pi \times (2.54)^2 \times (9 \times 10^5) \times \rho \times \text{P.F.}} \right]^{1/2}$,

where ρ = specific gravity of [illegible] and P.F. = packing factor of 0.76.

**Free open area = $(1-ND)^2$ where N = number of yarns per inch and D = yarn diameter (in.)

***Two yarn diameters.

†Three yarn diameters.

thick with a free open area greater than 30%, more than enough for the formation of rubber "bridges" through the structure during the final coating process.

To specify how much rubber should be applied to the fabric substrate for maximum flex resistance of the composite structure, some knowledge is needed of the influence of coating weight on flex lifetime. This question was not addressed as part of our study, but a determination of the effect of various coating amounts applied to a single fabric substrate would be invaluable for design of the optimum composite fabric.

Although the flex-fatigue behavior of Kevlar 29 itself in such a structure is not known, this material has been used successfully in rubber/fabric composites for which endurance of high-frequency flexing is required (automobile tires). The geometrical features of such a structure as reinforcement for SEV skirt material seem sufficiently attractive to warrant production of a full-scale trial fabric of this design.

SUMMARY AND CONCLUSIONS

The effect of fabric substrate design on the capacity of rubber-coated fabrics used in the construction of SEV finger panels to withstand high-speed, high-curvature bending deformation has been systematically studied. A series of fabrics was designed and produced which were composed of high-tenacity nylon yarns of 5040 or 10,080 denier containing fibers of either 2, 6 or 12 denier. The tensile strength requirement of 1200 lb/in. dictated a yarn density of 14 ends per inch in each direction of the 5040 denier fabrics and 7 ends per inch in the 10,080 denier fabrics. Yarn twist and yarn crimp level was varied between high and low levels, and both plain weaves and 3 x 3 twill and basket weaves were produced. All of the fabrics were scoured, heat-set, and rubber-coated on a platen press under identical conditions with the same natural rubber/polybutadiene blend applied to each after spray-coating with the same neoprene-based adhesive tie-coat. In this way, many composite fabrics were produced that were identical except for the structure of the substrate. The coated fabrics ranged between 70 and 80 oz/yd^2 in weight and 0.09 and 0.11 in. in thickness. Tensile strengths averaged about 1100 lb/in.

The flex-fatigue behavior of the various experimental fabrics was evaluated by means of a flex-testing device specially designed and built to subject fabric strips to relatively high-speed (15 Hz) and high-curvature (3.6 in.$^{-1}$) cyclic

bending in air. The results of the flex-cycling tests revealed a difference of more than two orders of magnitude in the number of cycles that composite materials could withstand before the appearance of flex-cracks in the rubber layer--from 140,000 to 21.7 million cycles, depending on the structure of the fabric substrate.

A factorial analysis of the flex-test results showed yarn denier, yarn crimp, and float-length to be the fabric construction parameters primarily important for determining flex lifetime: the lower yarn denier (5040), the lower levels of crimp, and the shorter float length (plain-weave) resulted in fabrics with significantly greater lifetimes in flex. No preference for the twill or basket-weave pattern in the longer float weaves was found.

The effects of fiber denier and yarn twist were not so straightforwardly evident because of the confounding effect of yarn crimp in the experimental design. However, interpretation of the results of the analysis of variance applied to several subsets of data involving various combinations of construction factors indicated that neither fiber denier nor the level of yarn twist had a significant main effect on flex lifetime.

Fabric structures in which both yarn denier and yarn twist are low tend also to have lower yarn crimp levels, lower knuckle height and, as a result, are thinner than fabrics of the same weight composed of higher denier, high twist yarns. When coated with the same weight of rubber, so that overall composite thickness is the same, the minimum thickness of the rubber layer covering the yarn knuckles will be greater in the fabrics with the thinner substrate than in those with a thicker one. Flex-testing of the experimental rubber/fabric composite materials provided evidence that resistance to flex-cracking is greatest in composites having a thinner fabric substrate. Greater thickness of the rubber layer in these structures, therefore, may be the reason that lower yarn denier and lower yarn crimp result in fabrics with greater flex lifetimes. However, such an interaction between fabric structure and thickness of the rubber layer cannot be separated in the current study from the effects that the various fabric construction parameters may have had on such factors as fiber bending strain and the number and nature of fiber intersections, which may also influence flex lifetime. Neither did we address the influence on flex lifetime of greater or lesser total amounts of rubber applied to the fabric substrates during manufacture.

No correlation was found between flex lifetime and either the flexural rigidity of the composite material or the level of adhesive bonding between rubber and substrate. However, independent studies at DTNSRDC of the behavior of rubber/fabric composite materials under impact revealed that good adhesion between rubber and fabric is necessary for high impact resistance. Fabric having a significant free open area to allow mechanical interlocking or "bridging" of the rubber layer through the substrate promote higher effective adhesive strengths. Unfortunately, such fabric structures are usually thick and they are the fabrics identified as having poor resistance to repeated flexing.

To take advantage of the greater impact resistance of the more open fabric constructions, three broad fabrics produced for full-scale skirt trials on the SRN4 Channel-crossing vessel were modelled after commercial fabrics having a high-twist, plied-yarn substrate structure. These fabrics have large pores for rubber strike-through. Two broad, plied-yarn fabrics were produced from 4 ply, 6720 denier, Type 728 nylon yarns which were plain-woven at 10 x 10 yarns per inch. One of these two identical fabrics was rubber calender-coated by Goodyear Aerospace Corp. and the other by the B. F. Goodrich Co., each of whom applied its own proprietary adhesive tie-coat formulations and natural rubber/polybutadiene blend of coating material. A third fabric consisting of 5880 denier, Type 728 yarn, wrapped rather than plied, was also woven in a 10 x 10 plain-weave construction and rubber-coated by Goodyear. This fabric attained about the same degree of openness as the plied-yarn fabrics but without the use of highly-twisted yarns. Limited laboratory flex-testing of these three trial fabrics in one direction only, showed better performance by the Goodrich-coated (4.4 million cycles) than the Goodyear-coated (1.2 million cycles) plied-yarn fabric. The wrapped-yarn fabric survived longer in the flex test (4.3 million cycles) than the similarly coated plied-yarn fabric (1.2 million cycles), probably because of the lower crimp of the yarns in the test direction of this fabric.

A fabric design is proposed which takes advantage of the higher intrinsic strength of Kevlar yarns to produce a thin, low crimp structure in which there is still significant free open area. A rubber/fabric composite containing such a fabric, plain-woven from 1500 or 2000 denier Kevlar yarns at 23 or 17 yarns per inch respectively, could combine the qualities of strength, flex and impact resistance needed by skirt materials for surface effect vehicles.

APPENDIX A
PROPERTIES OF TEST MATERIALS

TABLE A.1 - FORMULATION OF CONTROL ADHESIVE ECB-341

Ingredients	Parts by Weight
Neoprene GNA	100
Raven 1040 (carbon black reinforcer)	25
Hi-Sil 215	10
Sundex 790	5
Wingstay 100	1
Antioxidant 2246	1
Stearic Acid	0.5
STAN MAG-Beads (MgO - retardant)	4
Kadox-15 (ZnO - curing agent)	5
	Weight (%)
ECB-341	16
1,1,1-trichloroethane	84
Add 4% PAPI (isocyanate) just before use	

TABLE A.2 - FORMULATION OF CONTROL COATING ECB-502,
A NATURAL RUBBER/POLYBUTADIENE BLEND

Ingredients	Parts by Weight
SMR-5L (standard Malaysian rubber)	65
CIS-4 1203 (polybutadiene)	35
ISAF-LS (carbon black)	35
Hi-Sil 215 (silica - fine beads)	25
Sundex 790 (oil and plasticizer)	7
Medium Pine Tar (high viscosity plasticizer)	2
Cumar MH (resin)	4
Zinc Oxide (cure activator)	5
Stearic Acid (cure activator)	4.25
Sulfur (curative)	2.7
Santoguard PVI (retardant)	0.15
NOBS Special (delayed action accelerator, 280°F)	1
Agerite Hipar S (antiozonant/oxidant)	2
Antioxidant 2246	1
Cure Pressure: 100-700 psi (coating fabric)	
Slab Cure: 30 minutes at 300°F	

TABLE A.3 - PROPERTIES OF RUBBER/FABRIC COMPOSITES

Warp No.	Fabric Description	Thickness (in.)	Weight (oz/yd^2)	Tensile Strength (lb/in.)		Tear Strength (lb)		Peel Strength (lb/in.)		Flexural Rigidity* (lb-in.^{2}/in.)	
				Warp	Fill	Warp	Fill	Warp	Fill	Warp	Fill
I	Type 728 nylon, 6 dpf, 5,040 denier yarn, 14 x 14, low twist warp:										
	plain weave, low twist filling	0.105	81	--	--	--	--	--	--	0.062	0.065
	plain weave, high twist filling	0.105	81	--	--	--	--	--	--	0.076	0.074
	3 x 3 twill, low twist filling	0.103	79	--	--	--	--	--	--	0.057	0.060
	3 x 3 twill, high twist filling	0.103	81	--	--	--	--	--	--	0.069	0.060
	3 x 3 basket, high twist filling	0.105	82	--	--	--	--	--	--	0.075	0.083
	plain weave, low twist filling:										
	6 dpf, Type 704	0.096	76	--	--	--	--	--	--	0.058	0.055
	12 dpf, Type 704	0.103	80	--	--	--	--	--	--	0.071	0.074
	2 dpf, Type CO2	0.101	78	--	--	--	--	--	--	0.066	0.058
	6 dpf, Type CO2	0.104	78	--	--	--	--	--	--	0.066	0.046
III	Type 714 nylon, 6 dpf, 10,080 denier yarn, 7 x 7, low twist warp:										
	plain weave, low twist filling	0.103	80	1260	1070	630	590	28	32	0.073	0.071
	plain weave, medium twist filling	0.099	74	1300	1140	645	565	--	--	0.052	0.050
	plain weave, high twist filling	0.108	82	1140	1040	605	710	--	--	0.071	0.060
	2 x 2 twill, low twist filling	0.092	71	1230	1080	765	705	--	--	0.053	0.064
	2 x 2 basket, low twist filling	0.114	81	--	--	--	--	--	--	0.057	0.053
	2 x 2 basket, high twist filling	0.103	73	1350	1110	940	>1060	--	--	0.055	0.051
	3 x 3 twill, low twist filling	0.098	74	1270	1320	940	970	35	--	0.056	0.042
	3 x 3 twill, high twist filling	0.106	81	1190	1060	795	930	24	--	0.066	0.062
	3 x 3 basket, high twist filling	0.106	76	1180	940	915	1150	--	--	0.047	0.043
IV	Type 704 nylon, 12 dpf, 5,040 denier yarn, 14 x 14, high twist warp:										
	plain weave, low twist filling	0.103	71	--	--	--	--	--	--	0.033	0.034
	plain weave, high twist filling	0.103	76	--	--	--	--	26	--	0.048	0.041
	3 x 3 twill, low twist filling	0.099	77	--	--	--	--	--	--	0.051	0.052
	3 x 3 twill, high twist filling	0.102	79	--	--	--	--	--	--	0.056	0.052
V	Type 704 nylon, 12 dpf, 10,080 denier yarn, 7 x 7, low twist warp;										
	plain weave, low twist filling	0.099	69	1250	1160	530	530	23	35	0.053	0.042
	plain weave, high twist filling	0.102	75	1230	1130	525	715	23	23	0.048	0.056
	3 x 3 twill, low twist filling	0.105	78	1330	1020	1060	905	33;47**	26;48**	0.043	0.033
	3 x 3 twill, high twist filling	0.101	79	1170	900	625	840	--	--	0.040	0.030
	3 x 3 basket, low twist filling	0.091	67	--	--	--	--	21	25	0.046	0.041
VI	Type CO2 nylon, 2 dpf, 5,040 denier yarn, 14 x 14, low twist warp:										
	plain weave, low twist filling	0.101	76	--	--	--	--	21	25	0.053	0.054
	plain weave, high twist filling	0.102	78	--	--	--	--	--	--	0.055	0.057
	3 x 3 twill, low twist filling	0.100	77	--	--	--	--	--	--	0.050	0.066
	3 x 3 twill, high twist filling	0.100	78	--	--	--	--	--	--	0.056	0.048
VII	Type CO2 nylon, 2 dpf, 10,080 denier yarn, 7 x 7 high twist warp:										
	plain weave, low twist filling	0.106	77	--	--	--	--	41	43	0.045	0.049
	plain weave, high twist filling	0.109	79	--	--	--	--	43	42	0.050	0.049
	3 x 3 twill, low twist filling	0.104	76	--	--	--	--	--	--	0.060	0.053
	3 x 3 twill, high twist filling	0.103	77	--	--	--	--	--	--	0.052	0.056
	Goodyear Fabric XA28A504-2A	0.110	82	--	--	--	--	--	--	0.144	--

*At average radius of curvature of 0.25 inch.
**Represents two separate coating runs.

TABLE A.4 - FABRIC SUBSTRATE THICKNESS IN RUBBER/FABRIC COMPOSITES

Warp No.	Fabric Description	Average Substrate Thickness (in.)	Flex Lifetime, Filling Direction (million cycles)
I	Type 728 nylon, 6 dpf, 5040 denier yarn, 14 x 14, low twist warp:		
	plain-weave, low twist filling	0.050	>12.9
	plain weave, high twist filling	0.049	5.8
	3 x 3 twill, low twist filling	0.047	6.8
	3 x 3 twill, high twist filling	0.055	3.4
	3 x 3 basket, high twist filling	0.068	2.8
	plain weave, low twist filling:		
	6 dpf, Type 704	0.049	21.7
	12 dpf, Type 704	0.048	21.3
	2 dpf, Type C02	0.051	>17.1
	6 dpf, Type C02	0.048	19.4
III	Type 714 nylon, 6 dpf, 10,080 denier yarn, 7 x 7, low twist warp:		
	plain weave, low twist filling	0.053	2.2
	plain weave, high twist filling	0.071	0.9
	3 x 3 twill, low twist filling	0.055	0.8
	3 x 3 twill, high twist filling	0.071	0.4
	3 x 3 basket, high twist filling	0.075	0.3
IV	Type 704 nylon, 12 dpf, 5040 denier yarn, 14 x 14, high twist warp:		
	plain weave, low twist filling	0.053	3.6
	plain weave, high twist filling	0.059	1.0
	3 x 3 twill, low twist filling	0.051	0.8
	3 x 3 twill, high twist filling	0.065	0.8
V	Type 704 nylon, 12 dpf, 10,080 denier yarn, 7 x 7, low twist warp:		
	plain weave, low twist filling	0.064	5.8
	plain weave, high twist filling	0.084	2.3
	3 x 3 twill, low twist filling	0.064	1.0
	3 x 3 twill, high twist filling	0.056	1.1
	3 x 3 basket, low twist filling	0.058	1.3
VI	Type C02 nylon, 2 dpf, 5040 denier yarn, 14 x 14, low twist warp:		
	plain weave, low twist filling	0.050	10.9
	plain weave, high twist filling	0.052	4.4
	3 x 3 twill, low twist filling	0.051	1.5
	3 x 3 twill, high twist filling	0.058	2.1
VII	Type C02 nylon, 2 dpf, 10,080 denier yarn, 7 x 7, high twist warp:		
	plain weave, low twist filling	0.078	0.6
	plain weave, high twist filling	0.084	0.6
	3 x 3 twill, low twist filling	0.078	0.5
	3 x 3 twill, high twist filling	0.085	0.14

TABLE A.5 - COMPARISON OF PEEL STRENGTHS OF EXPERIMENTAL FABRICS COATED BY GOODYEAR AND ALBANY INTERNATIONAL (FILLING DIRECTION)

Fabric Construction	Peel Strength (lb/in. width)	
	Coated by Goodyear	Coated by AI
Warp V:		
plain weave		
low twist filling	27	35
high twist filling	38	23
3 x 3 twill		
low twist filling	33	26,48
Warp VI:		
plain weave		
low twist filling	32	25
Warp VII:		
plain weave		
high twist filling	36	42

APPENDIX B

PROCEDURES USED IN RUBBER/FABRIC COMPOSITE PREPARATION AND PRELIMINARY TESTING

FABRIC FINISHING PROCEDURES

Scouring

After completion of weaving the experimental fabrics were scoured to remove spinning oils and lubricants. Scouring was done at the Arkwright Finishing Plant, a division of United Merchants, in Fall River, MA. The fabrics were wound on perforated steel beams and immersed in a 500-gal bath at 160°F. The scouring solution consisted of 0.25% TSPP (trisodium pyrophosphate) and 0.1% Triton X-100, a non-ionic surfactant. The solution was circulated from the interior of the beam through the fabric layers at the rate of 1000 gal/min during the 30-min scour. Three hot 10-min rinses and one cold 10-min rinse followed at the same circulation rate. The fabrics were air dried. Chloroform extraction of the fabric before and after scouring revealed that the approximately 1% by weight of original spin finish was reduced to less than 0.02% by scouring.

Heat-Setting

In order to stabilize the fabric structure and prevent shrinkage during subsequent rubber lamination and curing, the fabrics were heat-set at 350°F., Setting was performed on a large through-air dryer at the Technical Fabric Division plant of Albany International in Auburn, ME. The dryer consists of an openly perforated, revolving drum, approximately four feet in diameter, through which hot air is forced at a controlled temperature and rate. The fabric remained in contact with the surface of the drum for a total time of 4 min during its passage over it at the rate of 1.5 ft/min; this was enough time for the fabric to reach the 350°F temperature of the hot air. Tension was applied in the warp direction of the fabric during setting to maintain length in that direction; no restraint was applied to prevent shrinkage in the filling direction.

Adhesive Application

The neoprene-based adhesive tie-coat formulation, ECB-341, with PAPI isocyanate curing agent (see Table A.1) was applied to the surface of the fabrics in the form of a spray. This method of application was chosen to provide uniform

cover and minimum penetration of the adhesive into the yarn structure of the fabrics. The sprayer used pumped the adhesive solution through a wide-angle nozzle at a uniform rate, but because the sprayer was operated manually some difficulties in maintaining a uniform covering layer were encountered.

Rubber Lamination

The fabric substrate was finally coated with metered layers of the natural rubber/polybutadiene blend, ECB-502 (see Table A.2) in an oil-heated Adamson platen press at the Technical Fabrics Division plant of Albany International in Buffalo, NY. The working surface of the press measured 90 in. by 10 ft. A layer of calendered rubber, nominally 0.030 in. thick, was cold-pressed onto each side of the fabric before curing in order to form a single sheet for ease of handling during the hot-pressing stage. The rubber/fabric composite was subsequently cured for 30 min at 300°F under a pressure of approximately 440 psi. The appearance of the finished product was excellent.

TENSILE STRENGTH TESTS

The rupture load of 2.0-in.-wide rubber-coated specimens was determined on an Instron tensile test machine using double-pin self-tightening jaws. The gauge length of the specimen between attachment points was approximately 12 in.; during the test the specimens were extended at the rate of 10 in./min. The target tensile strength of the fabrics was 1200 lb/in. width.

TEAR STRENGTH TESTS

The tearing strength of the coated specimens was measured by the Bird-wing tear method. The configuration and dimensions of the test specimen are shown in Figure B.1. During the tear test the yarns being ruptured are aligned in the direction of applied tensile load but are held only by the surrounding rubber matrix rather than being gripped directly in the jaws. The target tearing strength of the rubber-coated specimens was 60% of tensile strength, or approximately 720 lb.

FLEXURAL RIGIDITY TESTS

The bending stiffness of the various rubber-coated fabrics was determined from measurements of the force required to bend 1.25-in.-wide strips of each

fabric between flat, parallel plates. This test was performed on an Instron tensile test machine as illustrated in Figure B.2. An initial plate separation slightly more than 1/2 in. was gradually reduced to approximately 1/4 in. with the applied load continuously recorded. Calculations of flexural rigidty at an average radius of curvature of 0.25 in. (plate separation, 0.45 in.) are reported in Table A.3. These values were calculated according to the relationship:

$$G = \frac{PD^2}{2.85W}$$

where

G = flexural rigidity

D = plate separation minus fabric thickness

P = load at plate separation, D

W = specimen width.

EVALUATION OF BENDING HYSTERESIS LOSSES

Throughout the course of flex-cycling of most of the fabrics tested, the total force required to perform the flexing motion was monitored at each station (4 specimens per station) with a piezoelectric force transducer. Since bending hysteresis loss is proportional to this driving force[5], changes in hysteresis loss for the different fabric constructions can be easily followed as cycling proceeds. During cycling of Goodyear fabric XA28A504-2A, a significant increase in bending hysteresis loss was observed to accompany the initiation of flex-cracking in the material, as illustrated in Figure B.3. The typical trend for bending hysteresis loss for most of the fabrics in the experimental series is represented in Figure B.4. In most cases the bending hysteresis loss for the experimental fabrics decreased sharply at the outset of cycling and then either levelled off or continued to decrease gradually irrespective of the occurrence of flex-cracks or the increasing severity of damage. Some fabrics exhibited a more rapid decrease in hysteresis loss than that illsutrated in Figure B.4, but for only one construction was a gradual but slight increase observed. The overall level of hysteresis loss varied from 0.5 to 1.4 in.-lb/in. with no clear correspondence of level with particular construction features of the fabrics.

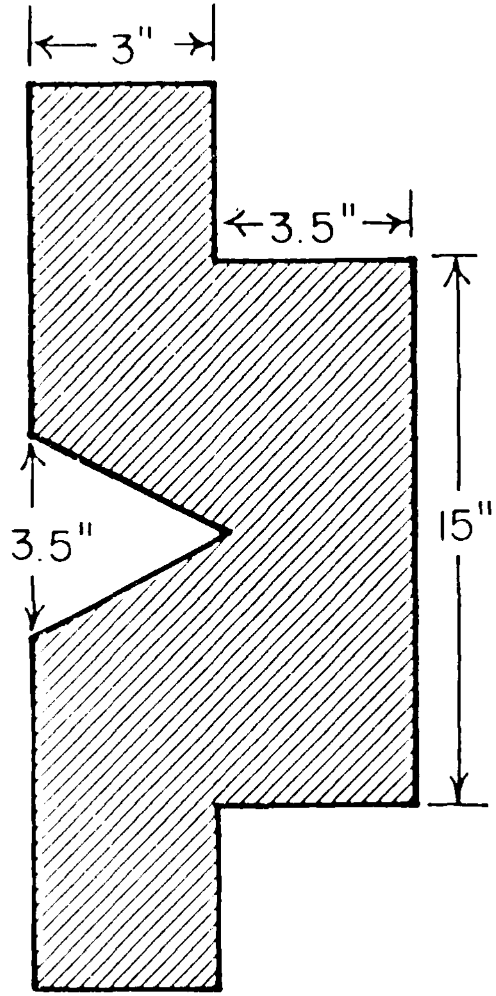


Figure B.1 - Bird-Wing Tear Specimen

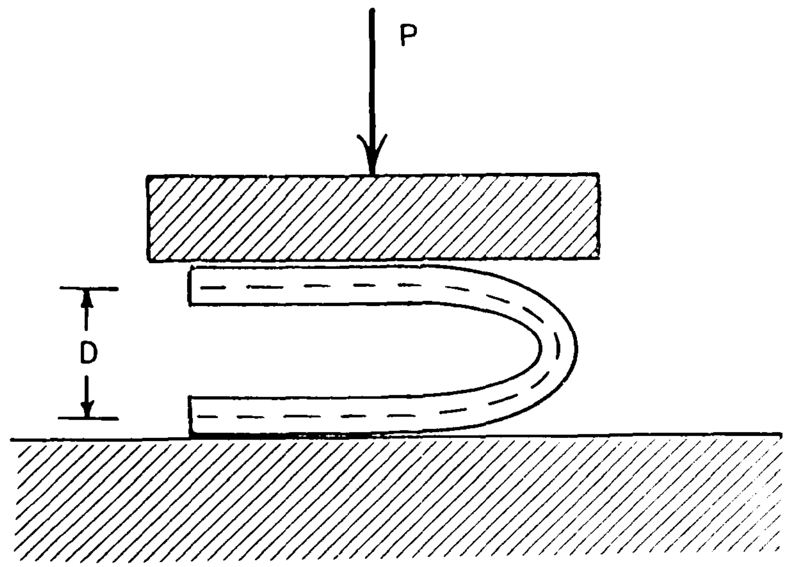


Figure B.2 - Specimen Configuration for Determination of Flexural Rigidity

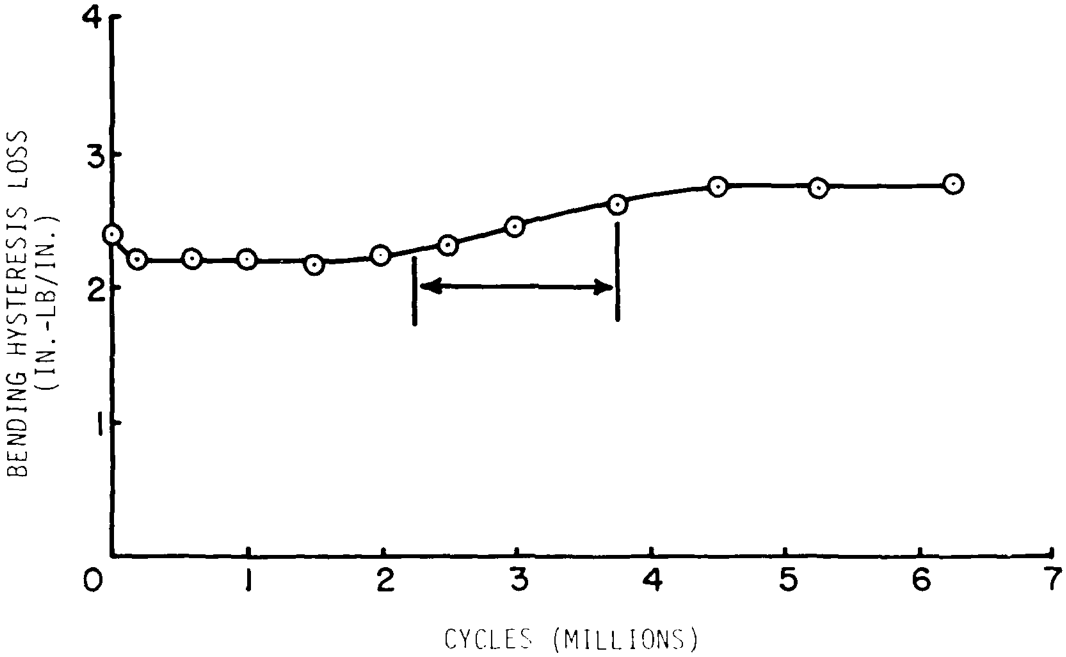


Figure B.3 - Trend in Bending Hysteresis with Continued Cycling for Goodyear Fabric XA28A504-2A

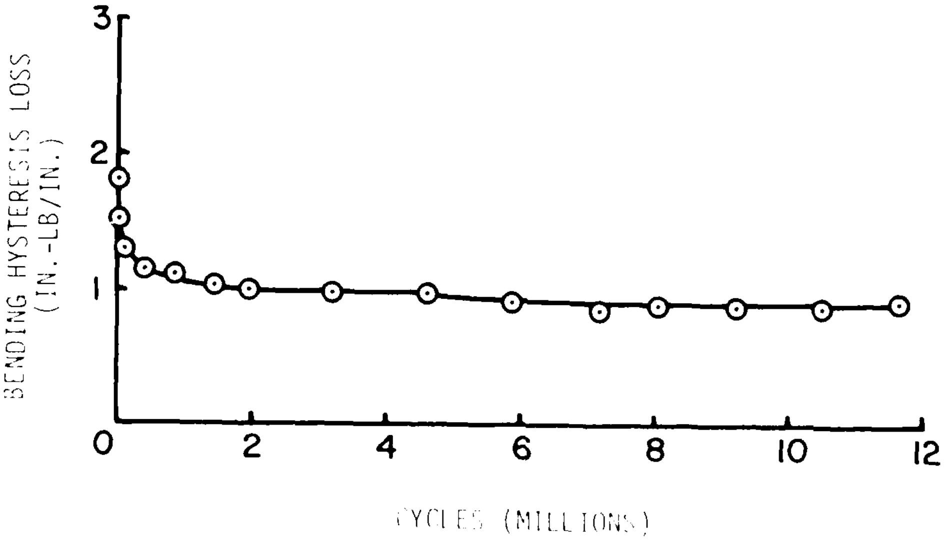


Figure B.4 - Typical Bending Hysteresis History for AI Rubber Coated Fabrics

APPENDIX C

FLEX LIFETIMES OF RUBBER/FABRIC COMPOSITES

TABLE C.1 - FLEX LIFETIMES OF VARIOUS EXPERIMENTAL RUBBER/FABRICS
(15 HERTZ; AVERAGE RADIUS OF CURVATURE, 0.28 IN.)

Warp No.	Fabric Description	[illegible]	[illegible] Direction	First Failure (millions of cycles) Individual	Avg.	Test Duration (million cycles)	[illegible]
I	Type 728 nylon, 6 dpf, 5040 denier yarn, 14 x 14 low twist warp:						
	plain weave low twist filling	0.105	warp	[illegible] 15.6 19.8 --	14.6	31.5	Cracking, tension side; not extensive
			fill	6.8 6.8 8.0 >30.0	>12.9	30.0	
	plain weave high twist filling	0.105	warp	4.1 6.7 10.7 13.6	8.8	30.0	Cracking, tension side
			fill	2.8 3.0 8.0 9.3	5.8	30.0	Same as above
	3 x 3 twill weave low twist filling	0.103	fill	2.8 5.2 9.7 9.7	6.8	30.0	Cracking, tension side
	3 x 3 twill weave high twist filling	0.103	fill	1.9 2.8 3.9 5.2	3.4	30.0	Cracking, tension side
	3 x 3 basket weave high twist filling	0.105	fill	2.4 2.4 2.8 3.6	2.8	3.6	Cracking, tension side
	plain weave [illegible] twist filling filling: Type 704, [illegible]	0.096	fill	22.6 [illegible] 14.6 [illegible]	21.7	31.5	Cracking, tension side; not extensive
	plain weave low twist filling [illegible] 12 [illegible]	0.103	fill	- [illegible] [illegible] [illegible]	21.3	31.5	Cracking, tension side; more extensive than above
	plain weave low twist filling filling: [illegible], 2 [illegible]	[illegible]	fill	[illegible] 26.[illegible] [illegible] [illegible]	[illegible]	31.5	Cracking, tension side, extensive one specimen only
	plain weave low twist filling filling: Type [illegible] 6 dpf	[illegible]	fill	[illegible] [illegible] 14.[illegible] 17.[illegible]	19.[illegible]	31.5	Cracking, tension side
III	Type 714 [illegible], 6 dpf, 10,080 denier yarn, 7 x 7, low twist warp:						
	plain weave low twist filling	0.103	warp	1.1 1.2 1.3 1.6	1.4	9.4	Cracking, tension side
			fill	2.2 2.2 2.2 2.4	2.[illegible]	11.6	Extensive cracking on tension side; some minor cracking on compression side
	plain weave high twist filling	0.108	warp	0.8 1.2 1.2 1.3	1.1	9.4	Extensive cracking, tension side; minor damage compression side
			fill	0.5 1.0 1.0 1.1	0.9	11.6	Extensive cracking on tension side
	2 x 2 twill weave low twist filling	0.092	fill	0.7 0.8 1.1 1.6	1.0	11.6	Extensive cracking on tension side; some minor cracking and buckling on compression side
	3 x 3 twill weave low twist filling	0.098	warp	1.5 1.5 2.3 2.3	1.9	10.0	Extensive damage, tension and compression side
			fill	0.5 0.8 0.9 1.0	0.8	11.6	Extensive cracking on tension side; severe damage on compression side

TABLE C.1 - FLEX LIFETIMES OF VARIOUS EXPERIMENTAL RUBBER/FABRICS (cont)
(15 HERTZ; AVERAGE RADIUS OF CURVATURE, 0.28 IN.)

Warp No.	Fabric Description	Thickness (in.)	Test Direction	First Failure (million cycles) Individual	First Failure (million cycles) Avg.	Test Duration (million cycles)	Ultimate Specimen Condition
III (cont	3 x 3 twill weave high twist filling	0.106	warp	1.5 1.5 1.5 1.9	1.6	10.0	Severe damage, tension side; some cracking & buckling, compression side
			fill	0.3 0.3 0.6 0.6	0.4	9.4	Extensive cracking on tension side, some damage on compression side
	3 x 3 basket weave high twist filling	0.106	fill	0.3 0.3 0.3 0.3	0.3	9.4	Severe cracking on compression side
IV	Type 704 nylon, 12 dpf, 5040 denier yarn, 14 x 14, high twist warp:						
	plain weave low twist filling	0.103	warp	5.5 9.5 >30.0 >30.0	>18.8	30.0	Extensive cracking tension side, no damage, compression side
			fill	1.3 1.6 5.1 6.2	3.6	10.0	Same as above
	plain weave high twist filling	0.103	warp	0.9 1.3 4.4 8.5	3.8	8.5	--
			fill	0.8 0.8 1.0 1.2	1.0	10.0	Extensive cracking tension side; no damage, compression side
	3 x 3 twill weave low twist filling	0.099	fill	0.15 0.15 1.3 1.6	0.8	10.0	Extensive damage, tension side-slight damage, compression side
	3 x 3 twill weave high twist warp	0.102	fill	0.15 0.15 1.3 1.6	0.8	10.0	Same as above
V	Type 704 nylon, 12 dpf, 10,080 denier yarn, 7 x 7, low twist warp:						
	plain weave low twist filling	0.099	warp	2.3 4.0 7.1 7.1	5.1	10.0	Relatively minor damage, tension side
			fill	4.8 4.8 6.2 7.5	5.8	9.3	Relatively minor damage, tension side
	plain weave high twist filling	0.102	warp	1.8 2.7 2.7 3.[illegible]	2.6	7.0	Minor damage, tension side
			fill	0.8 1.1 2.6 4.8	2.3	9.3	Extensive cracking tension side
	3 x 3 twill weave low twist filling	0.105	warp	1.9 2.3 2.3 2.3	2.2	10.0	Minor damage on tension side; extensive delamination on compression side
			fill	0.6 1.0 1.0 1.4	1.0	7.0	Some minor damage on tension side; severe damage on compression side
	3 x 3 twill weave high twist filling	0.101	warp	1.0 1.0 1.0 1.4	1.1	7.0	Extensive damage on tension side; some damage, compression side
			fill	1.0 1.0 1.0 1.4	1.1	7.0	Same as above
	3 x 3 basket weave low twist filling	0.091	fill	0.9 1.1 1.5 1.7	1.3	10.0	Cracking tension side; severe damage, some delamination, compression side

TABLE C.1 - FLEX LIFETIMES OF VARIOUS EXPERIMENTAL RUBBER FABRICS (cont)
[illegible], AVERAGE RADIUS OF CURVATURE, 0.25 IN.

Fabric No.	Fabric Description	Thickness (in.)	Test Direction	First Failure (million cycles) Individual	Avg.	Test Duration (million cycles)	Ultimate Specimen Condition
VI	Type [illegible] nylon, [illegible], [illegible] yarn [illegible] 14 x 14, low twist warp						
	plain weave low twist filling	0.101	warp	1.1 6.9 >10.0 >10.0	>7.0	10.0	Some cracking, tension side, no damage compression side
			fill	2.7 5.2 10.4 25.[illegible]	10.9	31.5	Extensive cracking, tension side
	plain weave high twist filling	0.102	warp	1.8 3.4 >10.0 >10.0	>6.3	10.0	Two specimens--some cracking tension side; two specimens, no damage
			fill	1.6 2.4 6.6 7.0	4.4	31.5	Extensive cracking; tension side
	3 x 3 twill weave low twist filling	0.100	fill	0.15 0.41 1.9 3.4	1.5	10.0	Severe damage, tension side; some damage, compression side
	3 x 3 twill weave high twist filling	0.100	fill	0.41 0.68 1.6 5.7	2.1	10.0	Same as above
VII	Type [illegible] 2 ply, 10[illegible] yarn, [illegible] x 2, high twist warp						
	plain weave low twist filling	0.106	warp	0.25 0.25 1.78 1.78	1.0	1.8	--
			fill repeat	(0.14 to 0.56) 0.30 0.25 <1.41 0.46	<0.60	0.3 10.0	Extensive cracking, tension side; some damage, compression side
	plain weave high twist filling	0.109	warp	0.24 0.34 0.78 1.18	0.6	1.8	--
			fill repeat	(0.14 to 0.56) 0.30 0.36 0.25 <1.41	<0.58	0.3 10.0	Extensive cracking, tension side, some damage, compression side
	3 x 3 twill weave low twist filling	0.104	fill	0.14 0.14 0.8 1.1	0.5	10.0	Extensive damage, tension and compression sides; fabric exposed
	3 x 3 twist weave high twist filling	0.103	fill	0.02 0.03 0.22 0.30	0.14	10.0	Extensive damage, tension side, some damage, compression side

TABLE C.2 - FLEX LIFETIMES OF VARIOUS COMMERCIAL RUBBER LAMINATED FABRICS
(15 HERTZ; AVERAGE RADIUS OF CURVATURE 0.20 to 0.28 IN.)

Fabric Description	Thickness (in.)	Test Direction	First Failure (million cycles) Individual	Avg.	Failure Mode	Test Duration (million cycles)	Ultimate Specimen Condition
Goodyear fabric; XA28A[illegible]-2A	0.110	warp	0.2-5.2 (see Table 8)	2.4	Cracking, tension side	8.0	Severe cracking and delamination, tension side
Goodyear fabric; XA28A[illegible]: thick rubber layer in tension	0.222	warp	~0.04	---	Cracking, compression side	0.12	Severe abrasive wear on compression side, fabric exposed
thick rubber layer in compression	0.222	warp	~0.03	---	Cracking, buckling and delamination, compression side	0.28	Severe abrasive wear associated with buckled inner layer; fabric exposed
Goodrich fabric; 1F[illegible]2-140	0.104	fill	1.3, 1.3 1.5, 1.7	1.4	Cracking, tension side	10.0	Extensive cracking, tension side; no damage, compression side
Avon fabric; [illegible]-HH	0.114	fill	0.6, 0.6 0.6, 0.6	0.6	Cracking, tension side	10.0	Extensive cracking, tension side; no damage, compression side

TABLE C-3 - FLEX LIFETIMES OF VARIOUS EXPERIMENTAL FABRICS COATED BY GOODYEAR
(15 HERTZ; AVERAGE RADIUS OF CURVATURE, 0.27 IN.)

Fabric Description	Thickness (in.)	Test Direction	First Failure (million cycles) Individual	First Failure (million cycles) Avg.	Test Duration (million cycles)	Ultimate Specimen Condition
AI Research Fabrics rubber-coated by Goodyear Aerospace						
Warp V: Type 704 nylon, 12 dpt, 10,080 denier yarn, 7 x 7, low twist warp:						
plain weave, low twist filling	0.122	fill	3.4 3.6 1.1 2.5	2.6	5.9	--
3 x 3 twill weave, low twist filling	0.136	fill	0.58 0.22 0.22 0.47	0.37	2.0	--
Warp VI: Type C02 nylon, 2 dpt, 5040 denier yarn, 14 x 14, low twist warp:						
plain weave, low twist filling	0.121	fill	>12.0 5.5 5.5 2.1	>6.3	12.0	Cracking, tension side, extensive delamination of two specimens on compression side
Warp VII: Type C0[illegible] 2 dpt, [illegible]10,080 denier yarn, [illegible] twist warp:						
plain weave, [illegible] filling	0.139	fill	0.33 0.13 0.47 0.47	0.35	2.0	--

TABLE C-4 - FLEX LIFETIMES OF BROAD FABRICS FOR TRIALS ON SRN4 CRAFT

[illegible]	Thickness (in.)	Test Direction	First Failure (million cycles) Individual	First Failure (million cycles) Avg.	Test Duration (million cycles)	Ultimate Specimen Condition
[illegible] 6120 total yarn denier, [illegible] 10 x 10; [illegible]year	0.137	warp	0.6, 0.7, 1.6, 2.0	1.2	10.0	Extensive cracking, both sides; delamination, compression side
		fill	1.1, 1.2, 1.4, 1.7	1.3		
[illegible]	0.142	warp	2.4, 2.4, 5.8, 7.1	4.4	10.0	Extensive cracking, tension side
		fill	2.0, 2.0, 4.4, 5.0	3.4		
Wrapped-yarn fabric, 5880 total yarn denier, plain weave, 10 x 10 (3) Coated by Goodyear	0.116	warp	1.1, 4.5, 4.5, 7.1	4.3	10.0	Cracking, tension side
		fill A	1.2, 1.2, 1.7, 2.0	1.5		
		fill B	1.2, 1.2, 1.2, 2.6	1.6		

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